NOAA Technical Memorandum OMPA-13

A SUMMARY OF KNOWLEDGE OF PUGET SOUND

RELATED TO CHEMICAL CONTAMINANTS

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DISCLAIMER

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PREFACE

This report was prepared for the MESA Puget Sound Project, Office of Marine Pollution Assessment, National Oceanic and Atmospheric Administration, as part of the Project's overall effort to determine the fate and effects of toxicants in Puget Sound. It was prepared by the authors under the direction and assistance of Mr. Edward Long, Project Biologist, NOAA/MESA Puget Sound Project, Seattle, Washington, under Contract No. NA79RAC00163.

The report constitutes a synthesis of available information on the marine ecosystem of Puget Sound intended to provide a synoptic representation of key processes and interrelationships which define the system. Although the material is presented within a systems framework, the report is structured according to disciplinary components to facilitate its use as an environmental guide and reference manual.

An array of diverse data generated by various researchers has been synthesized, integrated, and interpreted. To the extent possible, spatial and temporal trends in major ecosystem variables were documented. Quantitative synthesis of information was not always possible due to the large spatial and temporal variability of the data, the limited scope of current and past studies, and the lack of systems approach applied in historical studies which prohibited the development of specific ecological interpretations. Information gaps have been identified and presented within each chapter of the report. .

The Main Basin of Puget Sound and four subsystems (Elliott Bay, Commencement Bay, Sinclair Inlet, and Budd Inlet) have been examined with emphasis on the latter due to their proximity to land-based sources of toxicants and observed occurrences of biological abnormalities. For these systems, classical oceanographic information and environmental chemistry/fate data have been integrated to maximize the interpretational utility of the existing knowledge. In summary, the report provides information accompanied by an extensive list of references in a readily accessible format.

The intent of the report is to provide a technical reference for use in Puget Sound and for use in interpreting new NOAA-sponsored research results. The information contained in the report was obtained from published papers and documents and included very little preliminary or incomplete studies, hearsay, or speculation. Thus, as new information from ongoing and future research becomes available, some of the conclusions drawn in this report may be questioned, corroborated, or refuted.

EXECUTIVE SUMMARY

Puget Sound is a unique and highly complex ecological system. Temporal variability on scales from hours to years and short-range spatial differences make it difficult to develop a quantitative description of parameters and processes characterizing this region. This report deals primarily with the Main Basin and adjacent urbanized embayments. It identifies the major physical, biological, and chemical features of the system which have been studied sufficiently to provide at least a rudimentary understanding of the basic ecosystem relationships. Therefore, the information presented herein provides only a simplified overview of the distribution of variables and processes reflecting the long-term "average" conditions of the system. Firm conclusions and complete, accurate descriptions of many important processes could not be drawn from the information available at the time this report was prepared. This observation reflects the limited scope of current and past studies and the difficulty in generating specific ecological interpretations from data characterized by high spatial and temporal variability.

In spite of these limitations, the attempt to integrate all of the available information produced a number of interesting observations descriptive of the characteristics of the system. These are summarized below.

Physical Characteristics

Puget Sound is a fjord-like basin connected to the Pacific Ocean by the Strait of Juan de Fuca. There are several main subdivisions in Puget Sound including Admiralty Inlet, a sill area forming the northern boundary of the Sound; the Main Basin, a long, relatively straight basin; the Southern Sound, which consists of many inlets and channels; The Narrows, a sill area which connects the Main Basin and Southern Sound; and Whidbey Basin and Hood Canal, two large embayments connecting with the northern Main Basin. The latter two areas are not included directly in the study areas addressed in this report.

Circulation. Circulation in Puget Sound is estuarine in nature, being driven by freshwater inputs, gravitational convection, tides, and winds. The general circulation in the Sound can be described as a two-layer system with net northward (seaward) flow of lower salinity, less dense water in the upper layer and net southward (landward) flow of higher salinity, denser water in the lower layer. In Admiralty Inlet, the net seaward flow is larger than the net landward flow to compensate for freshwater inputs in Puget Sound.

The simple model of a two-layer system is complicated by mixing at Admiralty Inlet. A major portion of the seaward flowing upper layer is mixed downward into the lower layer and is refluxed back into the Main Basin. The lower layer is estimated to consist, on the average, of two-thirds upper layer water and one-third Strait of Juan de Fuca water. This mixture of water, forming deep Main Basin water, flows southward toward The Narrows, which acts as a "tidal pump" exchanging water between the Main Basin and Southern Sound. Tidal pumping at The Narrows produces upwelling of deep water and its incorporation into the seaward flowing surface layer, as well as a net clockwise circulation around Vashon Island. The two-layer estuarine flow regime found in most of Puget Sound is not present in this area because the tidal pumping induces net southward flow at all depths in East Passage and net northward flow at all depths in Colvos Passage.

This circulation pattern is further complicated by periodic intrusions of undiluted deep water from the Strait of Juan de Fuca. These intrusions can apparently occur at any time of the year in response to flood currents of long duration and/or large tidal range. An abundance of freshwater in the upper layer may prevent an intrusion from occurring by mixing with the incoming water, thereby significantly reducing its density. During intrusions, circulation and flushing in the Main Basin are increased; however, it is not known how much deep water is actually replaced during these intrusions. The major features of the net circulation in Puget Sound and major subregions are shown in Figures a and b.

Winds constitute another driving force for circulation. Predominantly from the south in the fall, winter, and spring, and predominantly from the north in summer, they affect the surface waters of Puget Sound and indirectly affect upper and lower layer circulation. Direct effects include wind waves and surface currents induced by wind stress. Southerly winds can enhance the seaward movement of the flowing upper layer, while northerly winds can retard this flow. Wind effects on surface circulation are probably most important in the embayments where the wind-induced surface circulation may at least temporally predominate over tidally induced flows.

Sedimentation. Sediments derived from shoreline erosion and from rivers are considered the major sediment sources to Puget Sound. The riverine sediment discharge was estimated to be 3.5×10^6 metric tons per year (mt/yr), while the sediment input from shoreline erosion was estimated to be 2.4×10^6 mt/yr. However, the contributions from these sources have not been fully elucidated. No sediment discharge data were available for many of the major rivers entering the Sound, and limited studies have been made of erosional losses from the shoreline. These limitations required several assumptions, e.g., as to the similarity of the sediment discharges for rivers of similar water discharges and the extent of eroding shoreline, to achieve these input estimates. As a result, the estimates may not be entirely accurate.
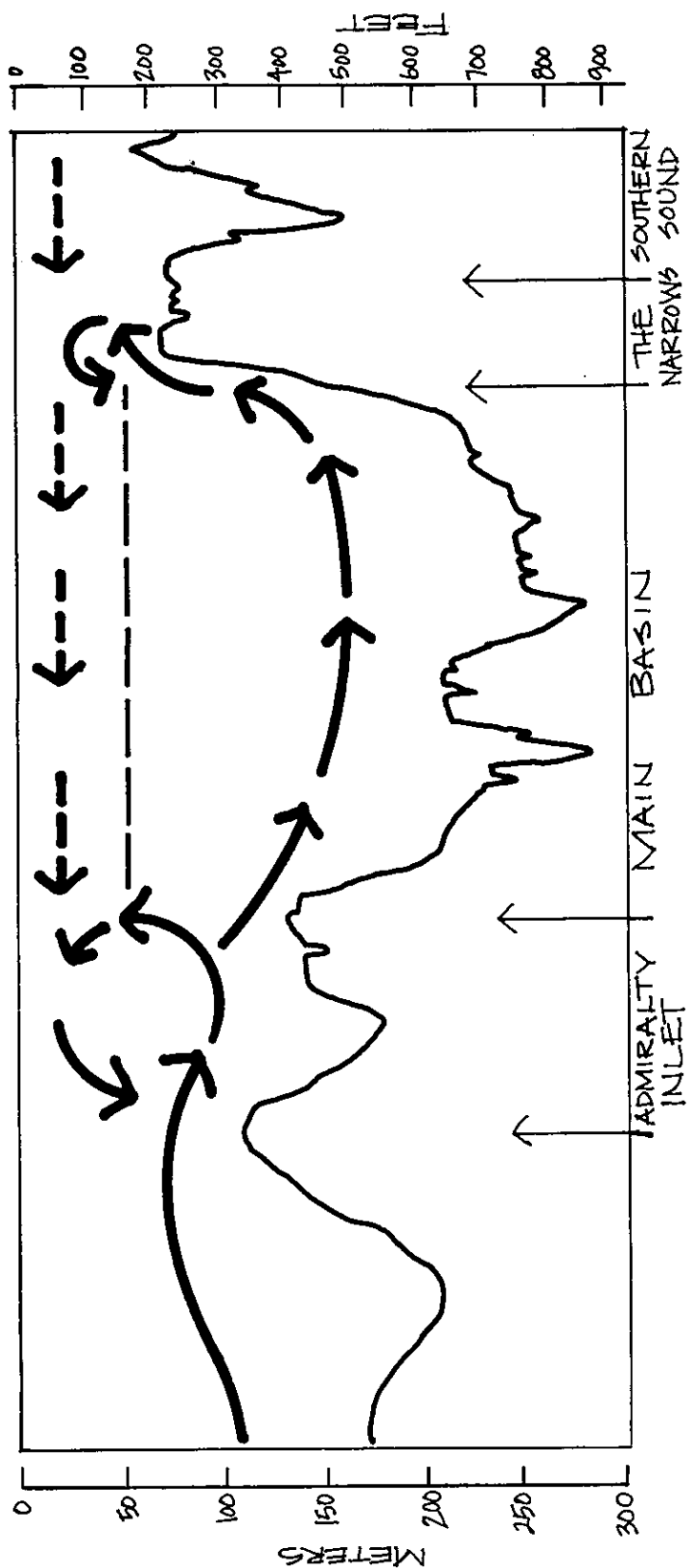
Figure a. Profile View of Net Circulation in Puget Sound. Dashed line indicates approximate depth of no-net-motion (50 m). Dashed arrows indicate surface, lower salinity flows; solid arrows indicate deep, higher salinity water movement.
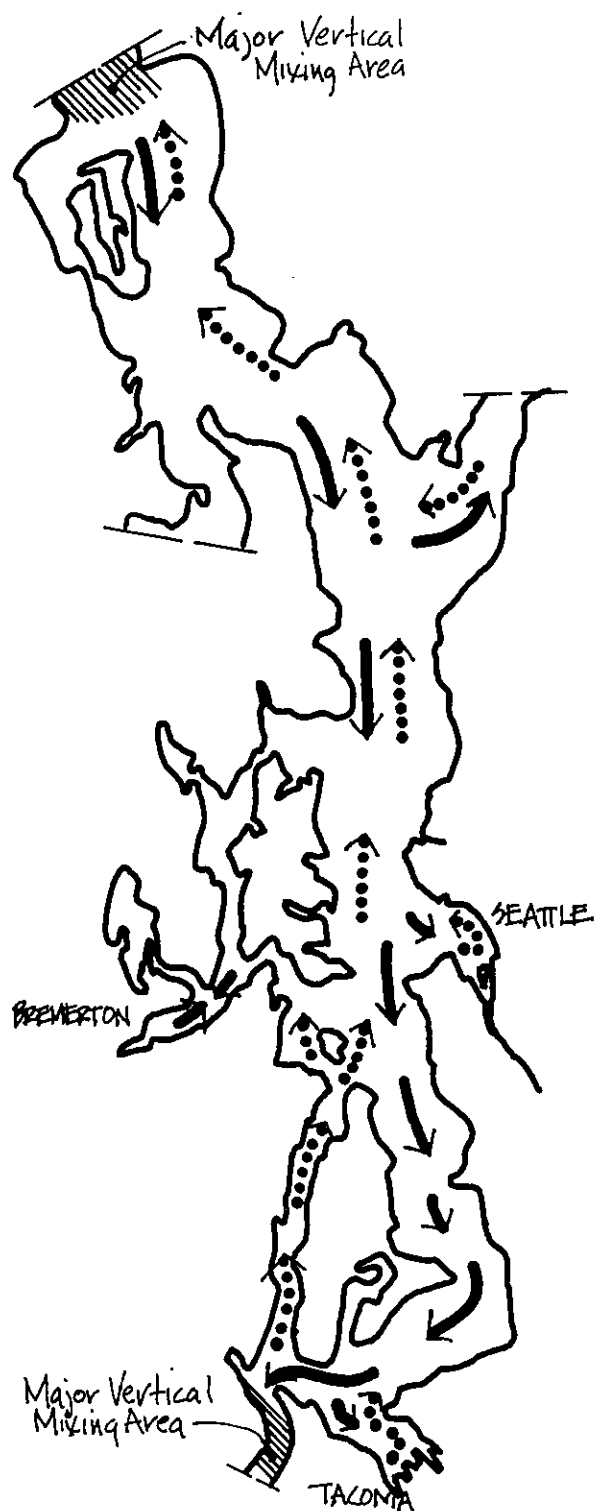
Figure b. Plan View of the Major Features of the Net Circulation in
the Main Basin of Puget Sound and in Elliott and Commencement Bays
and Sinclair Inlet. Length of arrows corresponds approximately to
the relative magnitude of the transports. Dotted lines indicate
surface, lower salinity flows; solid lines indicate deep, higher
salinity water movement.

Sedimentation rates derived from Pb^{210} dating range from 0.8 mm/yr to 20.0 mm/yr with an average rate of 6.1 mm/yr for the Main Basin. To achieve this rate, a sediment input of 1.7×10^7 mt/yr would be required, almost three times the estimated input. There are several possible explanations for this difference, the most probable being that the contribution from shoreline erosion is actually larger than what has been estimated.

The fate of sediments entering Puget Sound is dependent on circulation, turbulent mixing, flocculation, and resuspension. Sediment distributions in the Sound are a reflection of sediment sources and these transport conditions. Narrow channels have periods of strong currents and, as a result, are generally nondepositional areas with sand and gravel bottoms. Examples of these areas would include Admiralty Inlet, The Narrows, and Rich, Agate and Dana Passages. The embayments and very deep areas of the Sound have lower current velocities and, therefore, are depositional areas where the bottom sediments are primarily mud. Examples of these depositional areas would include Liberty, Elliott and Commencement Bays; Sinclair, Budd, Eld, Case and Carr Inlets; and the deep central part of the Main Basin.

Biological Characteristics

The dynamic circulation in a region otherwise protected from environmental extremes has led to the development of a productive and diverse ecosystem. At all trophic levels, different organisms exist which occupy the same or overlapping ecological niches. Thus, the system supports a fairly high degree of redundancy and is capable of rapidly adjusting to temporal changes.

However, this diversity and variability have also limited the elucidation of specific interrelationships among species and between species and their environment. For example, primary production has been partially characterized, with many of the dominant organisms identified, i.e., diatoms and dinoflagellates. The summer season of high production has been related to the increase in the effective light levels resulting from the combination of increased stability and insolation. The mean annual trends in phytoplankton standing stock as compared with the trends in major controlling variables are shown in Figure c. By and large, the rapid recycling of deep water to the euphotic zone eliminates nutrient limitations. At the same time, factors important in determining species dominance as well as the significance of smaller phytoplankton have received limited study.

Similarly, among sessile benthic organisms, spatial and temporal variability is large. Spatial differences appear to be related to the depth and characteristics of the sediments, but no distinct community assemblages associated with specific habitats have been identified. Temporal changes may result from alteration of the bottom characteristics and from seasonal variability in spawning and settlement success.
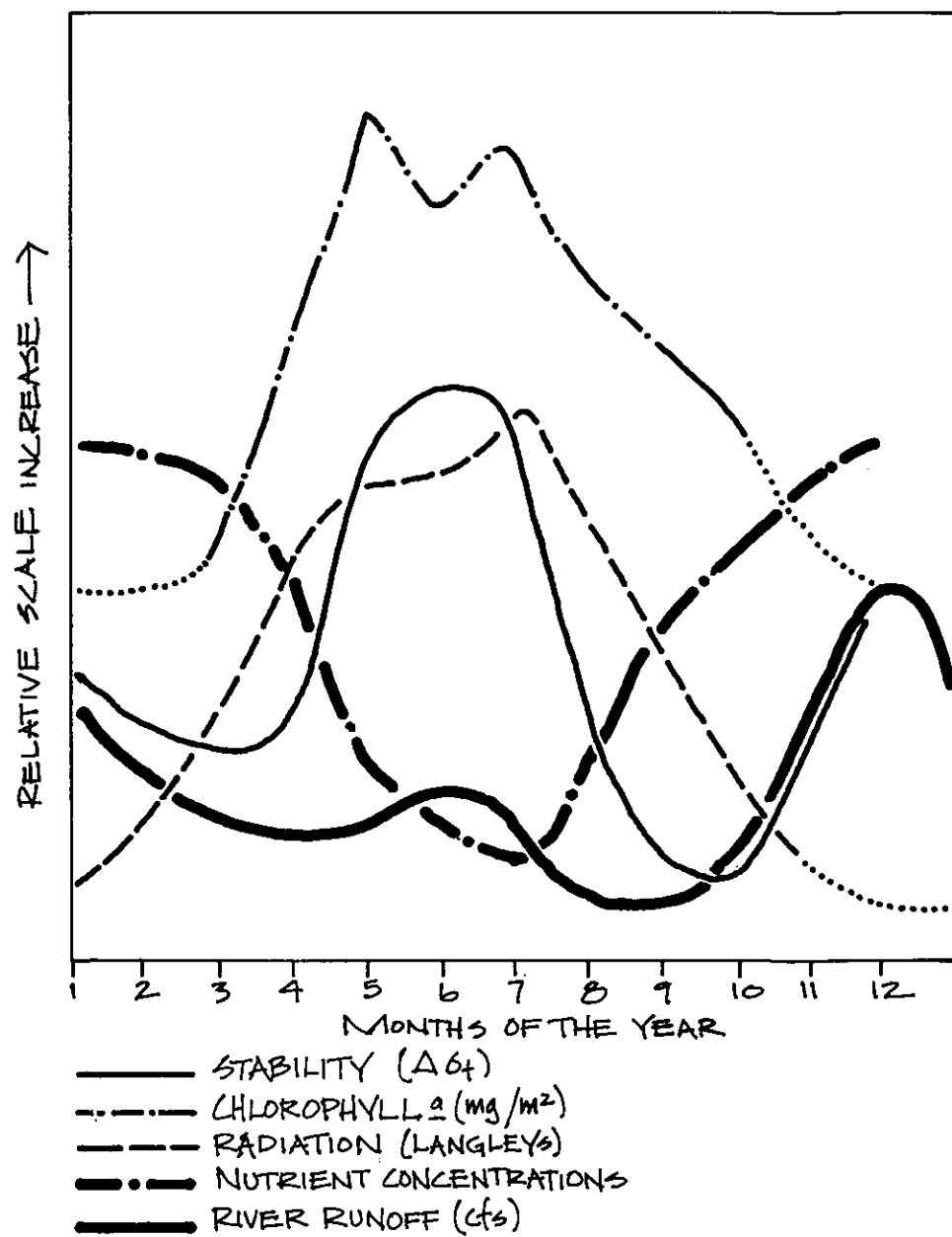
Figure c. Comparison of the Mean Annual Trends in the Phytoplankton Standing Stock with the Trends in Major Controlling Variables.

At higher trophic levels, few synoptic studies have been performed to examine either broad scale temporal or spatial trends or to determine trophic relationships among species. In general, the limited data provide evidence for an opportunistic food web in which organisms consume all available food within the size limits and capture strategy determined by the predator's feeding mechanisms. Food preferences of any·species may vary and appear to be largely determined by the relative availability of prey and the ease of capture.

Dynamics of Chemical Constituents

Trace Metals. At the present level of study, only arsenic (As), copper (Cu), lead (Pb), mercury (Hg), antimony (Sb), and zinc (Zn) appear to be associated with significant incidences of contamination. Overall, the data indicate that natural sources strongly dominate the inputs of these metals. In localized areas near urban development, however, high levels of the metals have been observed, particularly in the lower Duwamish River, the waterways of Commencement Bay and in Sinclair Inlet. High levels of As, Sb, Cu, and Zn are associated with the slag and effluent discharged from the smelter at Tacoma. While some specific sources have been identified for some metals, e.g., the smelter at Tacoma and a secondary lead smelter on Harbor Island, many of the sites with high concentrations of metals have not been clearly related to a source.

Transport and fate of trace metals in Puget Sound, including geochemical processes, have been poorly documented. The physical/chemical bases for these processes are well established in the literature, but a thorough study of the applicable reactions in the Sound has not been performed. Qualitatively, the metals tend to be preferentially associated with finer, organic-rich particles, and with the possible exception of Hg, are associated with the mineral phases of these particles. Mercury may be more strongly associated with the organic phase.

Organic Contaminants. A large number of toxic and potentially toxic organic compounds have been identified in Puget Sound or in discharges to the Sound. Of these only polychlorinated biphenyls (PCBs), chlorinated butadienes (CBDs), and polynuclear aromatic hydrocarbons (arenes) have received significant attention. In general, the distribution of these compounds is similar to those of the trace metals with high concentrations in the highly urbanized embayments. In contrast to the metals, however, the lower levels of organic contaminants found throughout the Sound appear to reflect transport from urban sources since no natural sources exist for most of these compounds. Distinct gradients in bottom sediments have been observed with high concentrations shown in areas close to sources.

Transport for these compounds is poorly understood except for PCBs. The available information for PCBs indicates that, in general, advective transport of contaminated water and particulates from the sources generates strong gradients within the urbanized embayments. Away from these areas, the dynamic mixing and recirculation of water in the Main Basin results in the ubiquitous contamination of all areas of the Sound at low and uniform levels. Physical/chemical processes were also shown to control transport.

Equilibrium partitioning, which maintains a constant ratio between the concentrations of the PCBs on the particulates and the concentrations in the water, was demonstrated to be the dominant mechanism influencing the distribution of PCBs in the water column and sediments. This sorptive/desorptive exchange has contributed to the overall contamination of the Sound by providing enhanced advective transport, which reflects the movement and mixing of the water rather than solely the deposition pattern of the particulates originating in the contaminated embayments.

Because of their general chemical similarities, the chlorinated butadienes and other nonpolar chlorinated organics and the arenes should behave similarly to the PCBs. Although limited, the data on the partitioning between water and suspended particulate matter support this conclusion.

Biological Abnormalities

Past research has documented the existence of histopathological abnormalities in biota of subregions of Puget Sound receiving considerable toxicant loads. The circumstantial evidence provided by this work suggests that ambient levels in certain areas of Puget Sound cause these effects. Although these abnormalities have been observed at greater frequencies within areas characterized by elevated concentrations of toxicants (Figure d), no direct evidence is available to verify the existence of a cause/effect relationship. In addition, there is no evidence whether any contaminants at their present concentrations in Puget Sound can induce individually or synergistically short-term acute effects (lethality) or long-term sublethal effects to the regional aquatic biota. If a cause/effect relationship indeed exists, then the carrying capacity of Puget Sound for certain toxicants or classes of toxicants has been exceeded.

Interpretive Overview

A conceptual representation of the dynamics of toxicants in Puget Sound and a rating of the relative importance of fate processes are provided. Only a few processes were found for which information is available to allow preliminary quantitation of the pathways of toxicants in the system. These processes are predominantly physical and chemical.
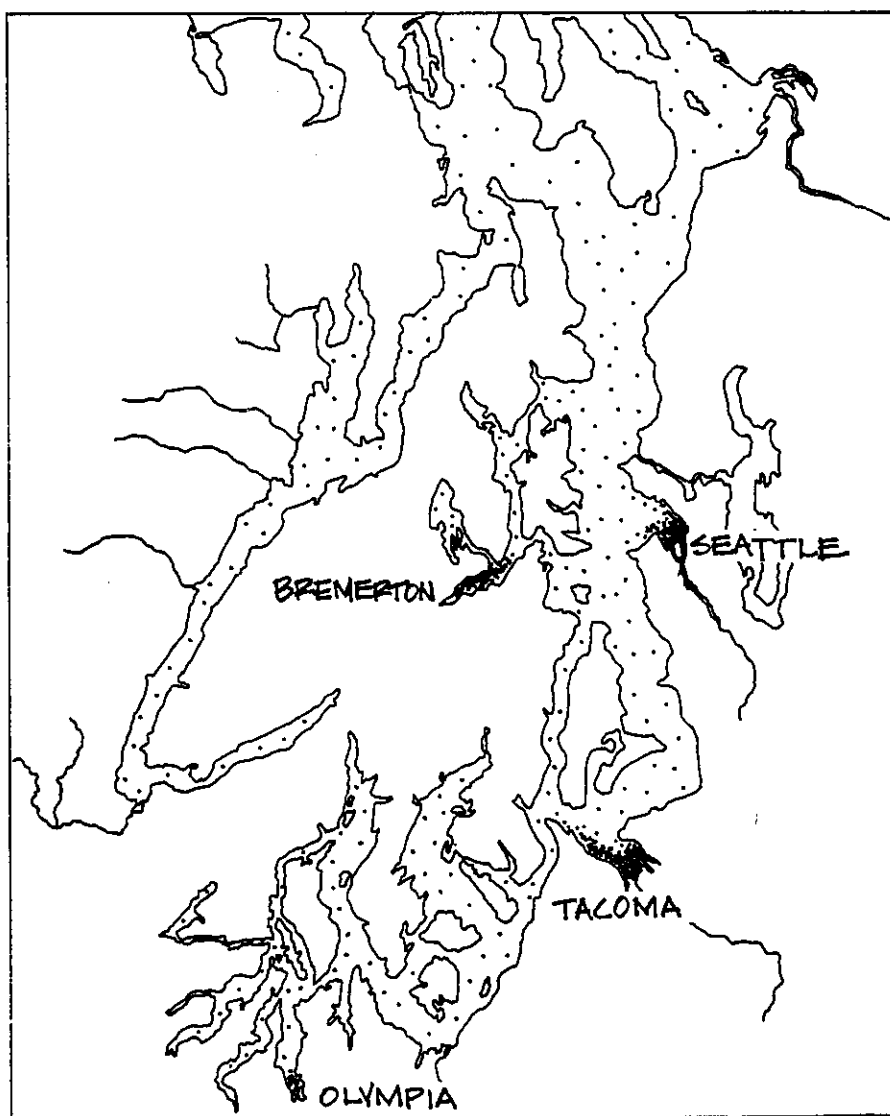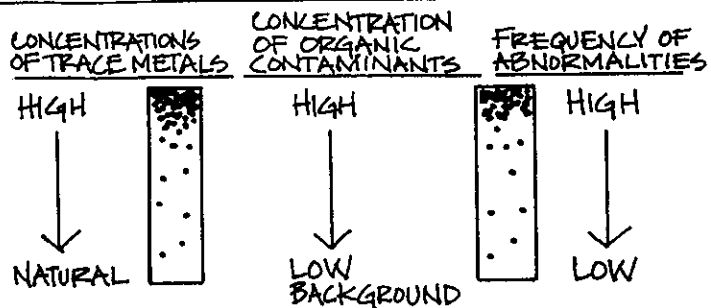
Figure d. Approximate Distributions in Puget Sound of Trace Metals, Organic Contaminants and Increased Incidences of Abnormalities in Benthic Organisms.

Based on the available information as presented in the ecological description of Puget Sound and the conceptual representation of transport and fate process, a generic scheme for determining the assimilative capacity of the system was developed. This scheme is intended to be used as a basis for future environmental research needed to acquire an understanding of the dynamics of toxicants in Puget Sound.

ACKNOWLEDGMENTS

CHAPTER 1. INTRODUCTION

Puget Sound is a dynamic estuarine system supporting a variety of valuable fisheries and commercial and recreational activities. Due to its limited municipal and industrial development, classical pollution impacts have rarely been observed and the region has generally been perceived as nearly pristine. However, recent studies have identified high concentrations of toxic trace metals and synthetic organic compounds in some areas of the Sound. These nonclassical pollutants pose a serious environmental threat to the health of the Puget Sound ecosystem.

The material presented in this report addresses primarily the status of knowledge of the Puget Sound marine ecosystems in terms of three interrelated elements of direct relevance to environmental concerns:

- Physical processes

- Biological characterization and ecological relationships

- Dynamics of toxic chemical constituents

The available data were integrated within an ecological framework to provide an overall understanding of the key processes and relationships which characterize this complex ecosystem. The analysis was based solely on those aspects which could be documented by past and ongoing research efforts. Unfortunately, the paucity of data in many instances has prohibited performing analyses within the complete and coherent framework desired.

It should also be noted that because this report was prepared in support of the NOAA/MESA Puget Sound Project Technical Development Plan to develop a program of studies to assess the effects of toxic trace contaminants, its scope is limited and biased. Primary consideration was given to the urbanized embayments of central and southern Puget Sound which are most impacted by human activities, and a major portion of the report considers in detail the available data on the distribution and fate of the trace contaminants. At the same time, the chapters dealing with the physical and biological aspects were prepared within a larger context of the overall characterization of Puget Sound. As such, these sections will provide useful information to all researchers and resource managers in the region.

The text is presented in a sequence starting with the description of the physical variables and processes which establish the ecological features of the Sound (Chapters 2, 3 and 4) and finishes with a

discussion of the distribution and fate of toxic metal and organic contaminants in the Sound (Chapters 8 and 9). The ecological discussion is presented in three separate subsections, the pelagic and benthic biota (Chapters 5 and 6) followed by an overview of trophic relationships (Chapter 7). Various histopathological and other biological abnormalities have been surveyed as possible indicators of an adverse response to chemical contamination. Results of these surveys have been assembled in Chapter 10.

Finally, Chapter 11 includes a conceptual representation of toxicant transport and fate, describing sources, input functions, toxicant forms, boundary processes, and contaminant flow pathways within the various marine components. This representation has been derived from the information contained in previous chapters. Components of the interactive scheme are cross-referenced with specific chapters where relevant information is presented.

CHAPTER 2. THE PHYSICAL SETTING

GEOGRAPHY

Puget Sound is a fjord-like basin located entirely within the State of Washington. It is connected to the Pacific Ocean by the Strait of Juan de Fuca (Figure II-1). There are three major topographic features in this region, the Cascade Mountain Range to the east, the Olympic Mountain Range to the west and the broad valley between them known as the Puget Lowland. This area has experienced at least four periods of glaciation resulting in the complex bathymetry observed in Puget Sound today.

There are several main subdivisions in Puget Sound (Figures II-1 and II-2). Admiralty Inlet is a sill area where Puget Sound joins the Strait of Juan de Fuca and forms the northern boundary of the Sound. The Main Basin of Puget Sound is a long, relatively straight basin with depths commonly exceeding 200 m. The Narrows, a sill area with a minimum depth of 44 m, is located at the southern end of the Main Basin. The Southern Sound consists of many inlets and channels with several fresh water sources, and connects to the Main Basin by The Narrows.

Other major subdivisions include Whidbey Basin and Hood Canal, which are not included in the study area addressed in this report. Whidbey Basin is located to the east of Whidbey Island. It is connected to the Main Basin at the southern end of Admiralty Inlet via Possession Sound. Deception Pass is at the northern end of the basin and connects to the Strait of Juan de Fuca. Two percent of the tidal prism for Puget Sound is exchanged through this narrow pass. Hood Canal is a long narrow inlet extending to the southwest from Admiralty Inlet.

GEOLOGY

Episodes of glaciations have had such a major effect on the Puget Lowland that it is difficult to reconstruct the preglacial structure of the area. Major features of the area were probably very much like they are today. The sheet of ice which covered British Columbia and extended south into the Puget Lowland is known as the Puget Lobe. As the glacier extended southward drainage into the Strait of Juan de Fuca was blocked and a large lake formed in the Puget Lowland. This lake eventually filled the entire Puget Sound drainage basin and spilled over into the Chehalis River Basin. For a short time the Puget Lobe occupied almost all of the Puget Sound drainage basin.
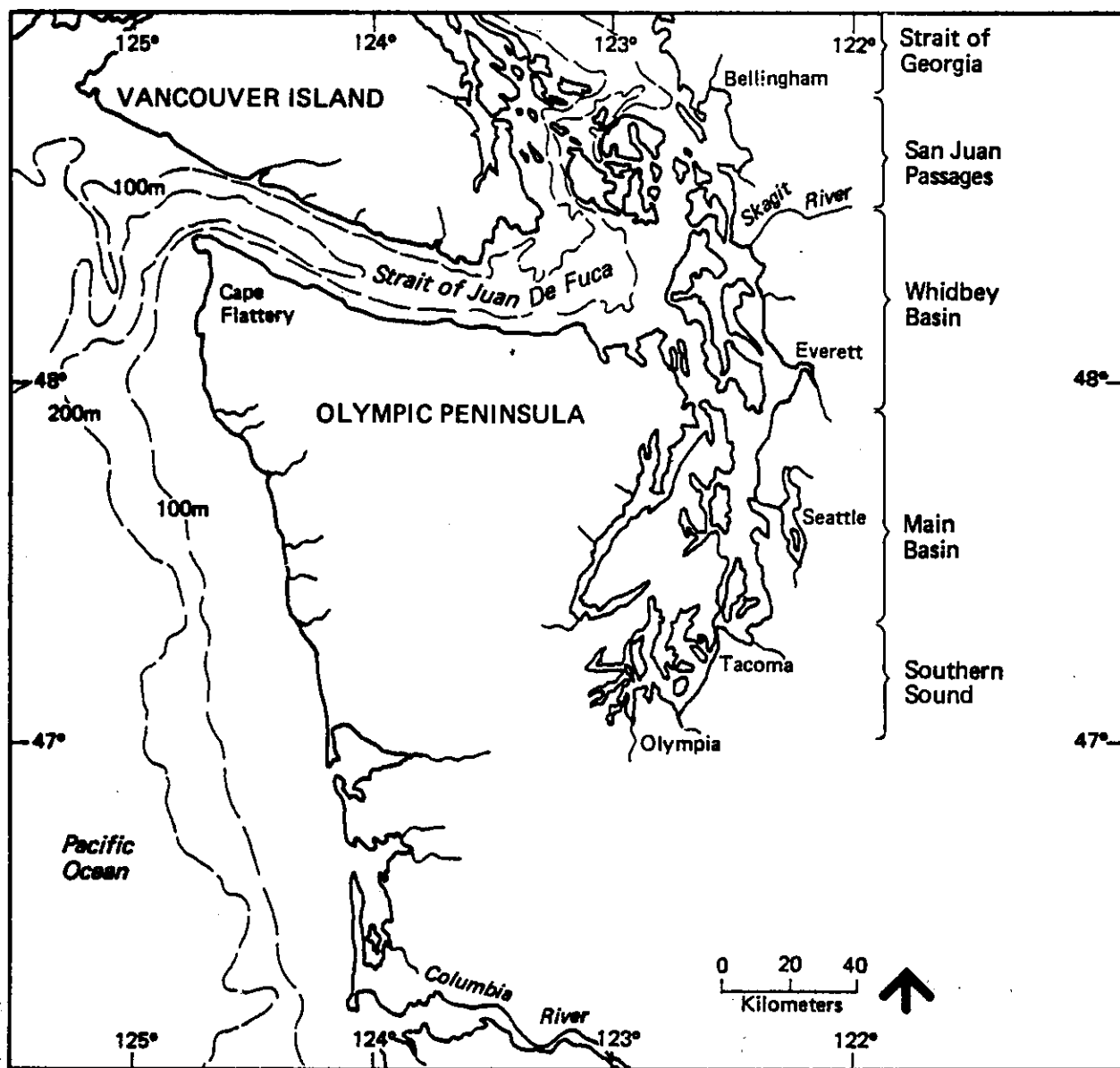
Figure II-1. Puget Sound and Approaches.
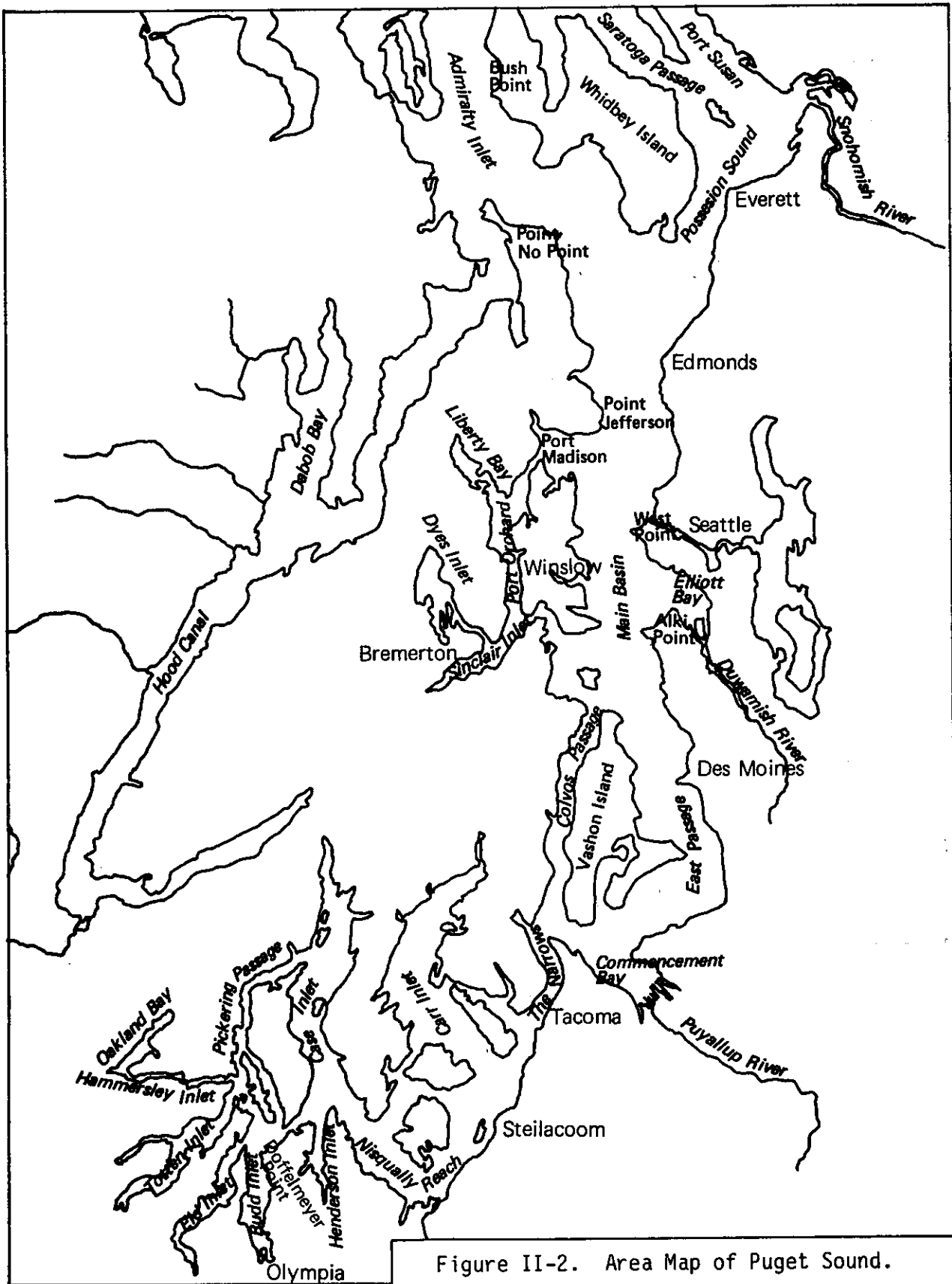
Figure II-2. Area Map of Puget Sound.

The advance and retreat of the glaciers produced a complex stratigraphic record. As the lake was formed, sediments carried by rivers into the lake were deposited. Coarse sands and gravels were deposited at the river mouths forming deltas. Finer material was carried farther into the lake before settling out. As the lake level rose, the river deltas retreated leaving the old deltas to be covered with finer sediments. This simple pattern of sedimentation was disrupted by the further advance of the glaciers. The edge of the glaciers provided meltwater runoff which acted like a river depositing coarse material near the advancing edge. As an area was overriden by a glacier some or all of the sediments deposited in the area could be eroded by the glacier. Sediments not eroded were greatly compacted (McKee, 1972).

In the Seattle area, evidence of only the most recent glaciation, which occurred 15,000 years ago, can be seen. The bluffs near West Point provide a good stratigraphic record. The base of the bluffs reveal a deposit of silts and clays called the Lawton Clays. Overlying this is the Esperance Sand deposit. These are topped by a layer of glacial till.

The combination of Esperance Sand on top of Lawton Clays makes these bluffs very unstable. Groundwater flows very easily through the sands but is absorbed slowly by the clays. Consequently, water collects near the boundary, mobilizes the sand and slumping occurs. These eroding bluffs are a major source of the sediments being deposited in Puget Sound at the present time.

CLIMATE

The major meteorological feature affecting the Puget Sound climate is the semi-permanent high pressure cell located over the eastern Pacific Ocean. During the summer this high pressure cell is located far enough north to produce northwesterly winds along the Washington coast. In autumn this high pressure cell weakens and moves south. The semi-permanent Aleutian Low then moves south so by mid-winter the prevailing winds are from the south.

Temperature

Normal daily maximum, average, and minimum temperatures recorded at Seattle are plotted by month in Figure II-3. The Puget Sound area does not experience the extreme range of temperatures which might be expected at this latitude. Normal daily minimum temperatures reach a low of 0°C (32°F) in January. The highest normal daily maximum temperature is 24°C (76°F) in July.

Fig. II-3

Fig. II-4

Fig. II-5
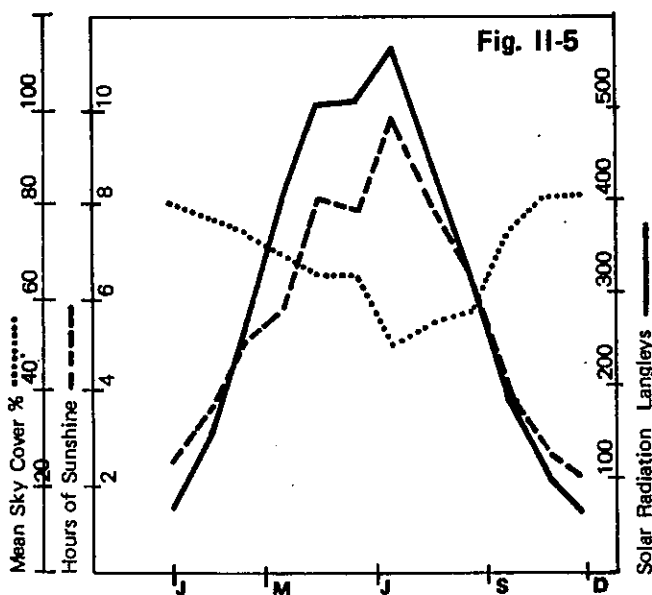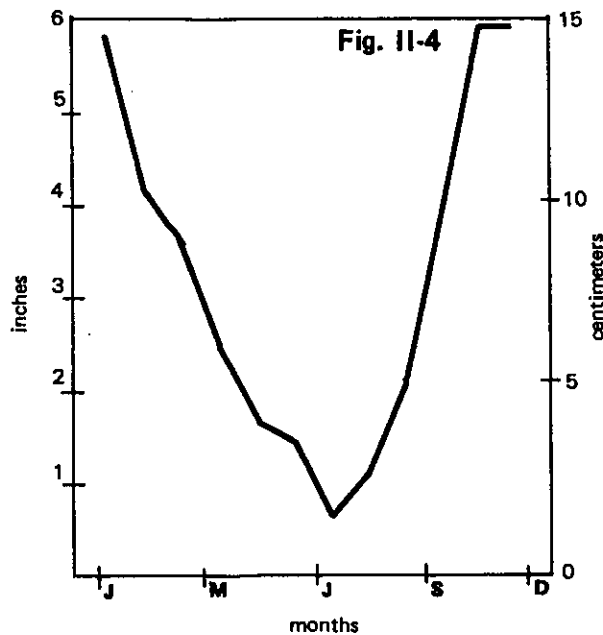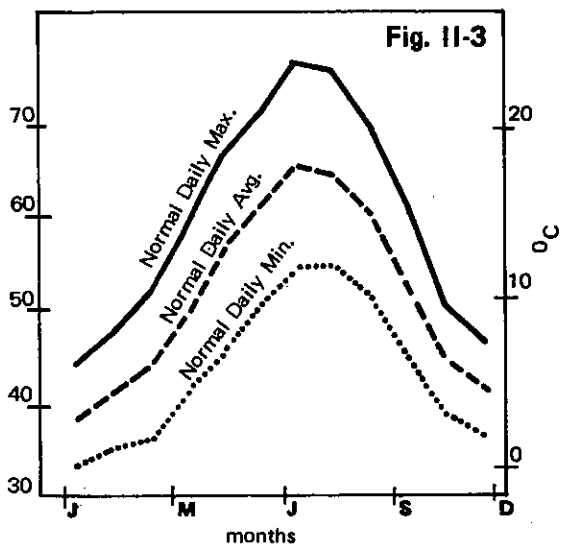
Figure II-3. Normal Daily Maximum, Average, and Minimum Temperature at
     Seattle by Month. Based on the 30-year period, 1931-1960.

Figure II-4. Average Monthly Total Precipitation at Seattle. Based on the
     30-year period, 1931-1960.

Figure II-5. Insolation Data: Average Monthly Values of Mean Hours of
     Sunshine per Day (‑‑‑), Mean Daily Solar Radiation in Langleys (——),
     and Percent Mean Sky Cover (·······). Based on the 30-year period, 1931-1960.

Source: Environmental Data Service, 1968.

Precipitation

Average monthly total precipitation measured at Seattle is shown in Figure II-4. In general, the Puget Sound area experiences a summer dry period coincident with the presence of the semipermanent high pressure cell off of the coast. The winter wet period occurs at the time of southerly winds produced by the Aleutian Low.

Insolation

Average monthly values, measured at Seattle, for three types of insolation data are shown in Figure II-5. These are: 1) the mean number of hours of sunshine per day, 2) mean daily solar radiation (langleys), and 3) mean percentage of sky cover. The Puget Sound area experiences the most sunshine and solar radiation, and least sky cover in July. This is also the month of least precipitation and highest air temperatures. In December the most sky cover and least radiation and sunshine occur. December also has the most precipitation and second lowest temperatures.

Winds

Surface winds over Puget Sound have been analyzed by Harris and Rattray (1954). The general patterns which they described are summarized below and shown in Figure II-6. Local topography can significantly change the direction of the wind in a local area.

December-March. Winds off the southern Washington coast are southerly to southwesterly. Moving north along the coast the winds turn to become southeasterly off of Estaban Point on Vancouver Island. Winds over Puget Sound are southerly from Olympia to Bellingham. Winds are from the east in the Strait of Juan de Fuca and Strait of Georgia.

April-May. This is a transition period when winds shift from southerly to northerly. Over the Southern Sound winds are usually southerly. However, over Admiralty Inlet winds tend to be predominantly from the north.

June-September. Through the summer the prevailing northerly winds, present over Admiralty Inlet in May, extend south into the Sound. By September northerly winds are well established at Tacoma. During this period Olympia and Tacoma experience a high percentage of calm winds. Olympia experiences about equal amounts of northerly and southerly winds.

October-November. Winds over the entire Puget Sound region return to southerly. This shift occurs much more rapidly than the shift from southerly to northerly in the spring.
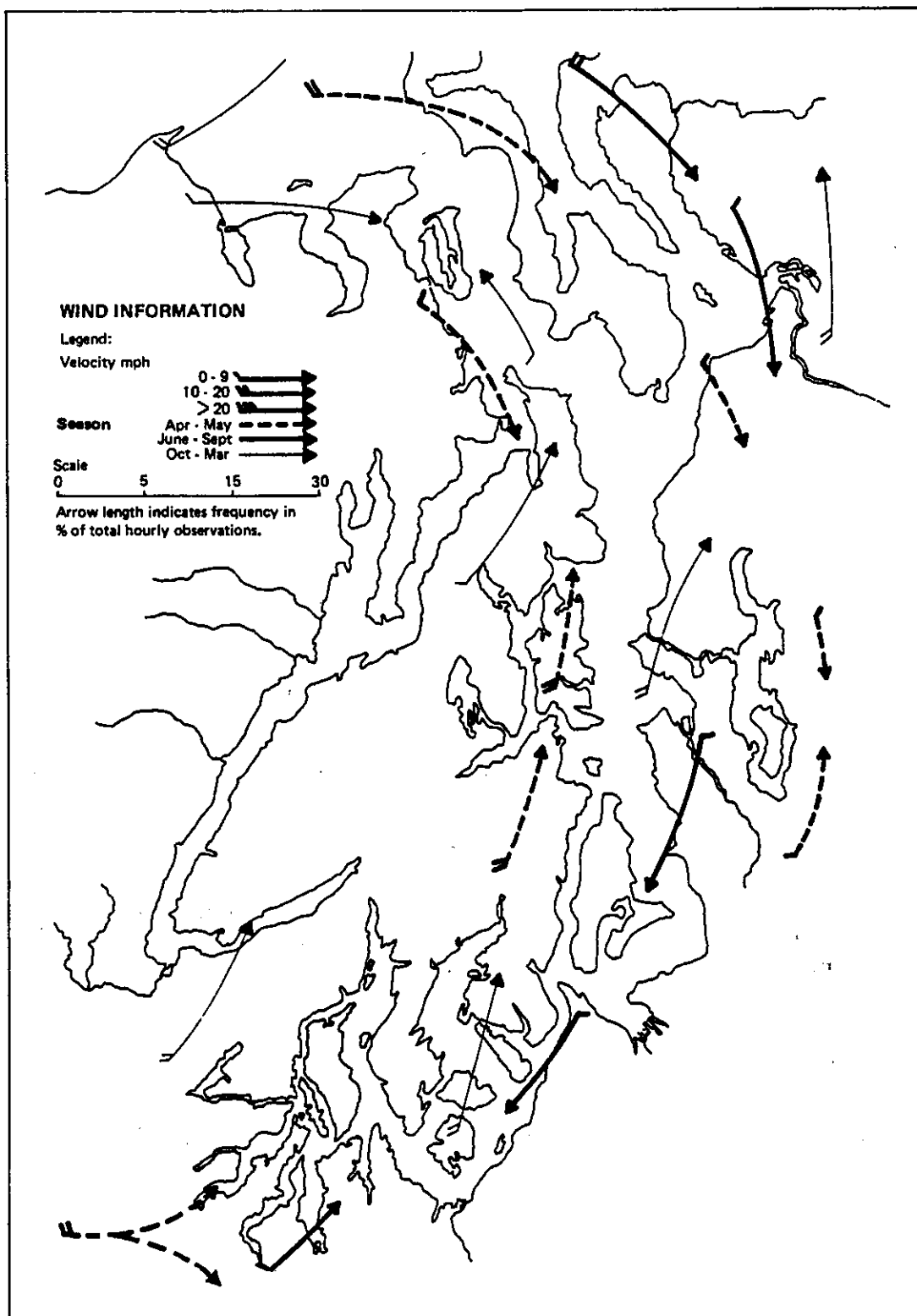
Figure II-6. Surface Winds in the Puget Sound Region.

Source: Harris and Rattray, 1954.

TIDES

The National Ocean Survey (NOS) publishes annual tables of tides and tidal currents (NOS, 1980a,b). Publications for the west coast of North and South America include two reference stations in Puget Sound where daily predictions are made and many other stations where tidal differences are given.

Tides in the Puget Sound region are of the mixed type with a strong diurnal inequality. Table II-1 lists several tidal parameters for locations in Puget Sound. Times of high and low water (H.W., L.W.) relative to when they occur at Seattle represent the phase lag of the tide through the Sound. It takes 23 minutes for an average high tide to travel from Point No Point to Tacoma and then 24 minutes to travel from Tacoma to Olympia. Tide ranges tend to increase from north to south. Due to the geomorphology of the Sound, flood and ebb tides and slack water are not always directly related to the tide stage. At some locations, tidal currents reverse directions one to two hours before or after high or low water. Greatest speeds are observed in narrow passages connecting larger areas of the Sound, e.g., The Narrows, Colvos Passage, and Admiralty Inlet. In many areas, tidal currents are too weak and variable to be predicted.

RUNOFF

Three of the largest rivers discharging into Puget Sound discharge into Whidbey Basin. Of all the runoff entering Puget Sound, including Whidbey Basin and Hood Canal, approximately 65 percent discharges into Whidbey Basin. Two-thirds of the Whidbey Basin discharge enters the Main Basin just south of Admiralty Inlet, while the remaining one-third discharges through Deception Pass. The Southern Sound and Hood Canal each receives about 10 percent of the total discharge. The Main Basin receives the remaining 15 percent (Ebbesmeyer and Barnes, 1980).

Annual average discharge values for the major rivers in the Puget Sound region are presented in Table II-2. Five year averages of mean monthly discharge values for these rivers are shown in Figure II-7. Rivers discharging into the Main Basin and Southern Sound generally follow the annual cycle of precipitation. The Skagit and Snohomish Rivers drain higher elevations than do the other rivers and they also exhibit a snowmelt peak in May or June. This snowmelt runoff provides a large portion of the total summer freshwater input to Puget Sound.

TABLE II-1

TIDAL INFORMATION INCLUDING TIMES OF HIGH (H.W.) AND LOW (L.W.) WATER, MEAN RANGE, DIURNAL RANGE, MEAN TIDE LEVEL, AND AVERAGE MAXIMUM FLOOD AND EBB CURRENTS FOR SEVERAL LOCATIONS IN PUGET SOUND

Place	Time of H.W. (Min)	Time of L.W. (Min)	Mean Range (m)	Diurnal Range (m)	Mean Tidal Level (m)	Average Maximum Velocity (m/sec) Flood Speed	Flood Dir.	Ebb Speed	Ebb Dir.
Port Townsend	---	---	1.6	2.6	1.6	Weak and Variable			
Bush Point, Admiralty Inlet	---	---	1.7	2.7	1.6	0.9	140	1.5	310
Point No Point	-16	-16	2.0	3.2	1.9	---	---	---	---
Edmonds	-5	+2	2.2	3.3	2.0	0.1	170	0.3	000
Port Madison	-8	-8	2.3	3.5	2.0	Weak and Variable			
Seattle	0	0	2.3	3.4	2.0	Weak and Variable			
Des Moines	+3	+9	2.4	3.6	2.1	0.2		0.2	
Tacoma	+7	+6	2.5	3.6	2.1	Weak and Variable			
The Narrows	---	---	----	----	---	1.6	135	1.4	335
Steilacoom	+22	+35	2.9	4.0	2.3	---	---	---	---
Nisqually Reach	+24	+42	2.9	4.1	2.3	0.6	260	0.6	045
Dofflemyer Point	+29	+47	3.2	4.4	2.5	0.4	235	0.2	030
Olympia, Budd Inlet	+31	+46	3.2	4.4	2.5	Weak and Variable			

TABLE II-2

ANNUAL AVERAGE DISCHARGE VALUES FOR THE MAJOR RIVERS
IN THE PUGET SOUND REGION (in cubic meters per minute, m³/min)

River	Five Year Mean* (m^3/min)	Long-Term Mean (m^3/min)	Number of Years in Long-Term Mean	Discharges Into
Skagit	26,640	28,560	38	Whidbey Basin
Snohomish	16,299	17,194	15	Whidbey Basin
Puyallup	5,408	5,753	64	Main Basin
Stillaguamish	5,068	5,065	50	Whidbey Basin
Duwamish	2,577	2,632	18	Main Basin
Nisqually	2,182	-	-	Southern Sound

* Five year mean values computed from daily values for water-years 1974 through 1978.

Sources: U.S. Geological Survey (USGS), 1975, 1976, 1977, 1978 and 1979.
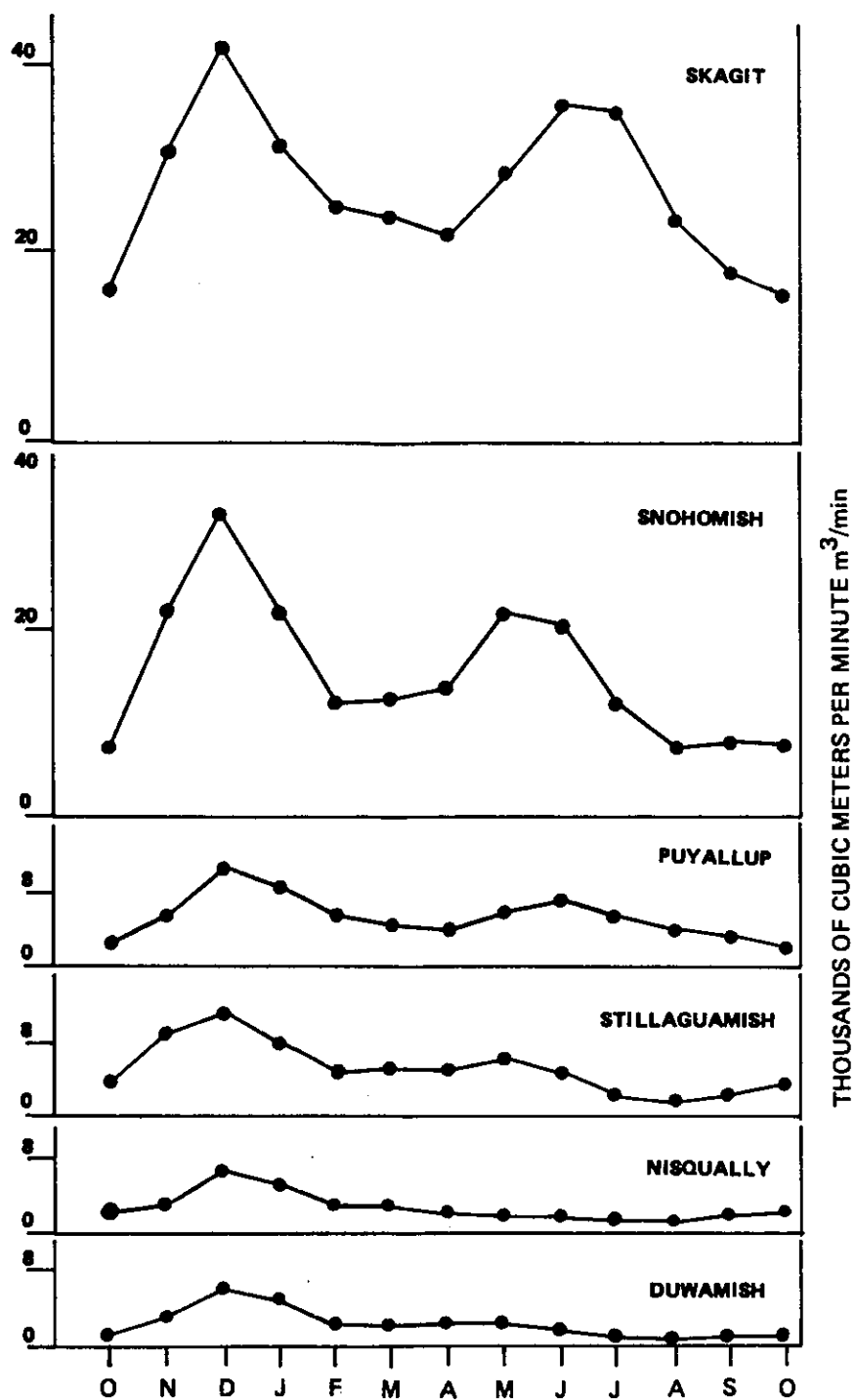
Figure II-7. Mean Monthly Discharge Values for the Major Rivers in the Puget Sound Region. Based on the 5-year period, 1974-1978.

Sources: USGS, 1975, 1976, 1977, 1978, 1979.

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CHAPTER 3. CIRCULATION

MAIN BASIN

DISTRIBUTION OF WATER PROPERTIES

Distributions of water properties reflect surface conditions, source waters, and circulation processes. Water properties were sampled on a fairly regular monthly schedule at select stations throughout Puget Sound from 1932 through 1975. Detailed accounts of this work can be found in Collias (1973) and Collias et al. (1974) and are summarized below. The long time period over which these data were collected has provided a large data base for describing the normal or average distributions of salinity, temperature, density, dissolved oxygen (DO) and phosphate. The station locations through the Main Basin and the corresponding bottom profile are shown in Figure III-1.

During the summer, upwelling along the Pacific Coast brings cold, saline water, having low dissolved oxygen and high nutrient concentrations, closer to the surface. This water enters the Strait of Juan de Fuca and moves through Admiralty Inlet supplying bottom water to Puget Sound. The most dense water in the Strait of Juan de Fuca is present in the summer. However, as this water moves through Admiralty Inlet it mixes with less dense surrounding surface and deep waters. As a result, the time of maximum density, high nutrient concentration and low DO in the Main Basin does not occur at the same time as it does in the Strait. The temporal and spatial distributions of water properties are described below. The mechanisms controlling these distributions are discussed further in the circulation section.

Temporal Distributions

The temporal distributions of water properties discussed below and shown in Figure III-2 are considered to be representative of Main Basin water and are based on samples collected at the Point Jefferson station. Water below 50 m depth at this station was considered representative of deep Main Basin water.

Salinity. Deep water salinity reaches a maximum in October and a minimum in March (Figure III-2). Surface water salinities are also at a maximum in October but the minimum occurs in June. Secondary maximums and minimums occur in April and February, respectively. The surface to bottom range in salinity is lowest in October and highest in June.
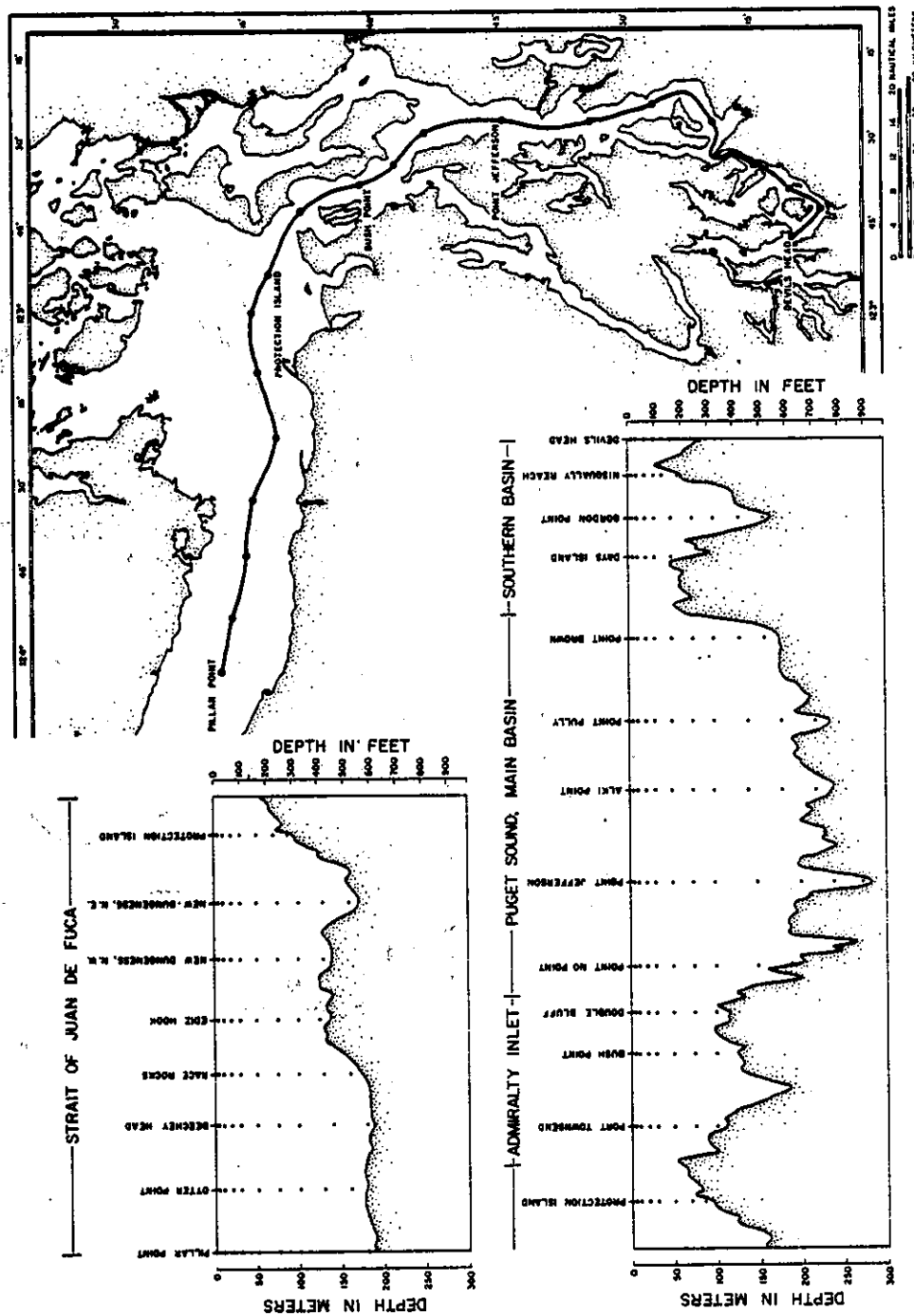
Figure III-1. Station Location Map and Bottom Profile from Pillar Point to
Devils Head. Station locations are represented by dots on the map.
Sampling locations are represented by dots on the vertical profile.

Source: Collias et al., 1974.
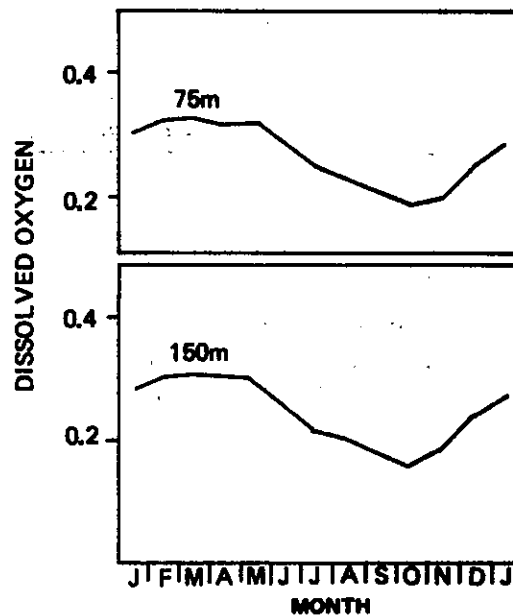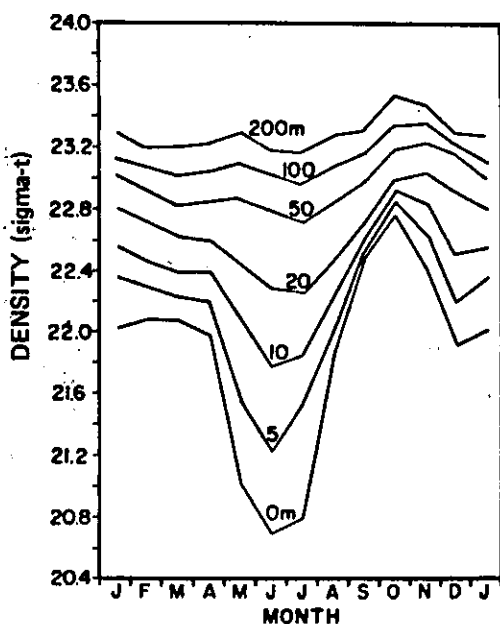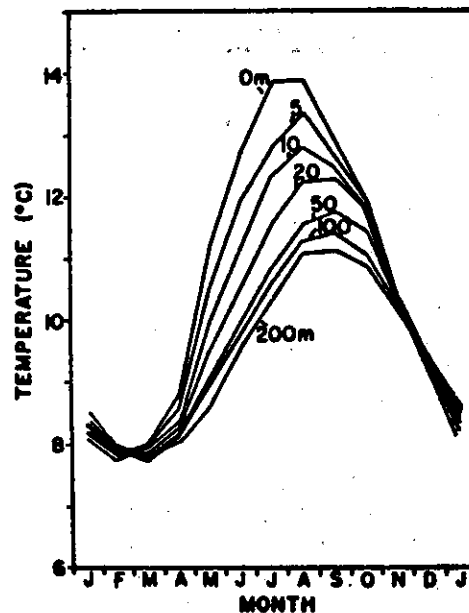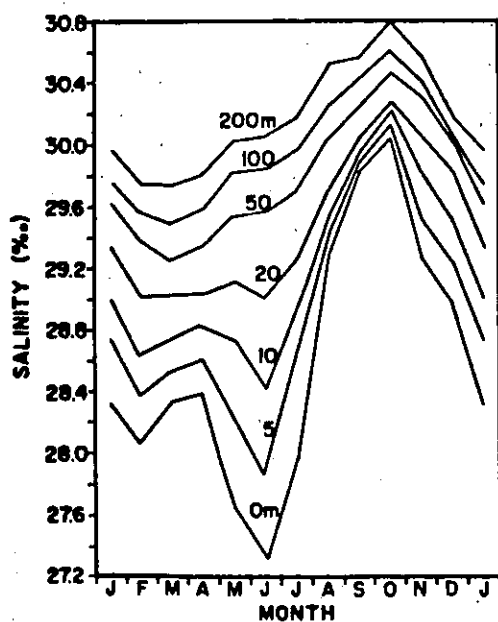
Figure III-2. Yearly Cycles of Monthly Mean Temperature, Dissolved Oxygen, Salinity and Density for Standard Depths at Point Jefferson. Based on data from the period, 1932-1975.

Sources: Ebbesmeyer and Barnes, 1980; Helseth et al., 1979.

Temperature. Surface temperatures are maximum in July or August
with minimum values for both surface and deep water occurring in February
or March. Maximums of deep water temperatures occur in September. The
range in surface to bottom temperature is greatest in August.

Density. Density in the deep water of the Main Basin is primarily
determined by salinity. The vertical density and salinity profiles have
similar shapes. The effect of temperature is to raise or lower density
without a major effect on the vertical density structure. The greatest
range in density occurs in June.

Dissolved Oxygen. Dissolved oxygen is at a maximum of over
0.5 mg-at/l from February through May. DO concentrations decrease to a
minimum of approximately 0.4 mg-at/l in September or October then rise
again to their maximum value in February. The surface to bottom range
in DO concentration is largest in May thru July due to primary produc-
tion in the surface waters and respiration at depth.

Phosphate. Phosphate values for deep Main Basin water (not shown
in Figure III-2) range from approximately 1.4 to 3.0 µg-at/l. Average
maximum values of approximately 2.7 µg-at/l occur in October or November.
Values remain high through the winter then decrease in the spring.
Average minimum values of less than 2.0 µg-at/l occur in June.

Spatial Distributions

Along-Channel Variations. Vertical sections of water properties
taken along the transect shown in Figure III-1 are presented in Figures
III-3 through III-7. Sections are shown for early spring and autumn.
In general, water of any depth becomes warmer, less saline and less
dense moving from north-to-south through the center of the Main Basin.
Deep water oxygen values also decrease to the south. Deep water phos-
phate values increase somewhat toward the south.

Cross-Channel Variations. Measurements of surface water properties
(not shown here) taken during the summer along transects between
Bremerton and Seattle and between Winslow and Seattle showed variations
which were several times greater than the along channel variations
(Helseth et al., 1979). During this study, colder more saline surface
water was observed on the west side of the Main Basin. This higher
density water was thought to be the water discharging through Colvos
Passage.

Cross channel variations in the deep water and at other times of
the year have not been documented.
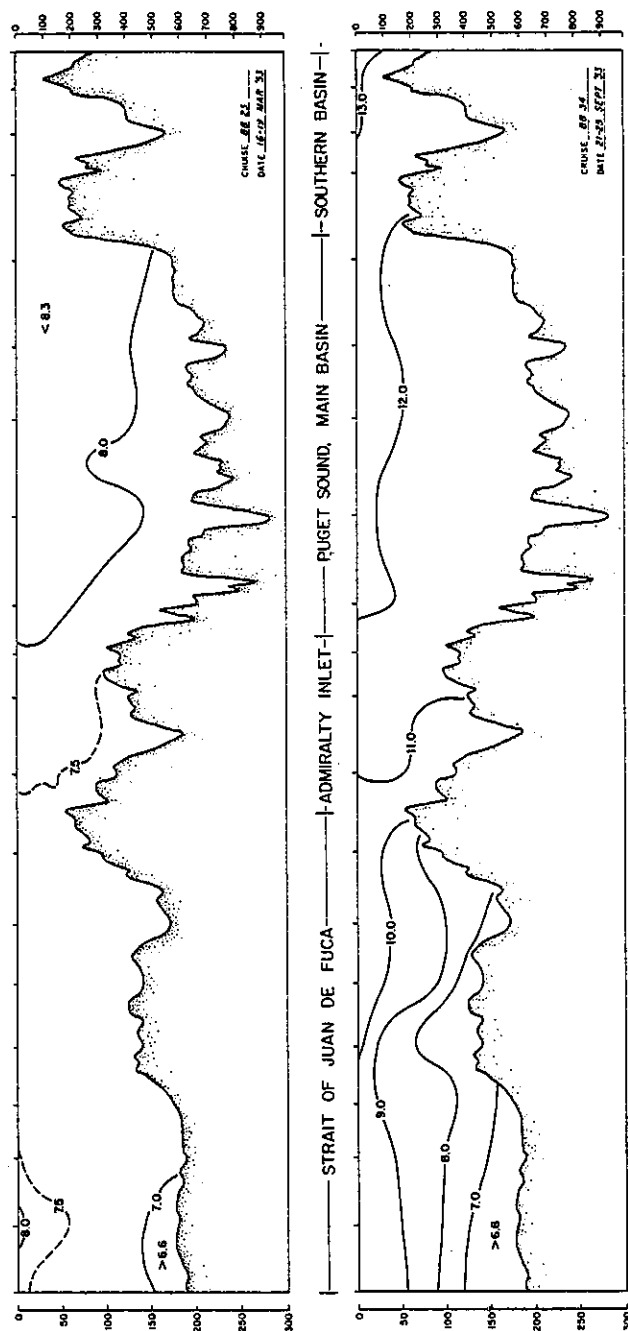
Figure III-3. Vertical Sections of Temperature (°C) Through Puget Sound, March and September 1953.

Source: Collias et al., 1974.
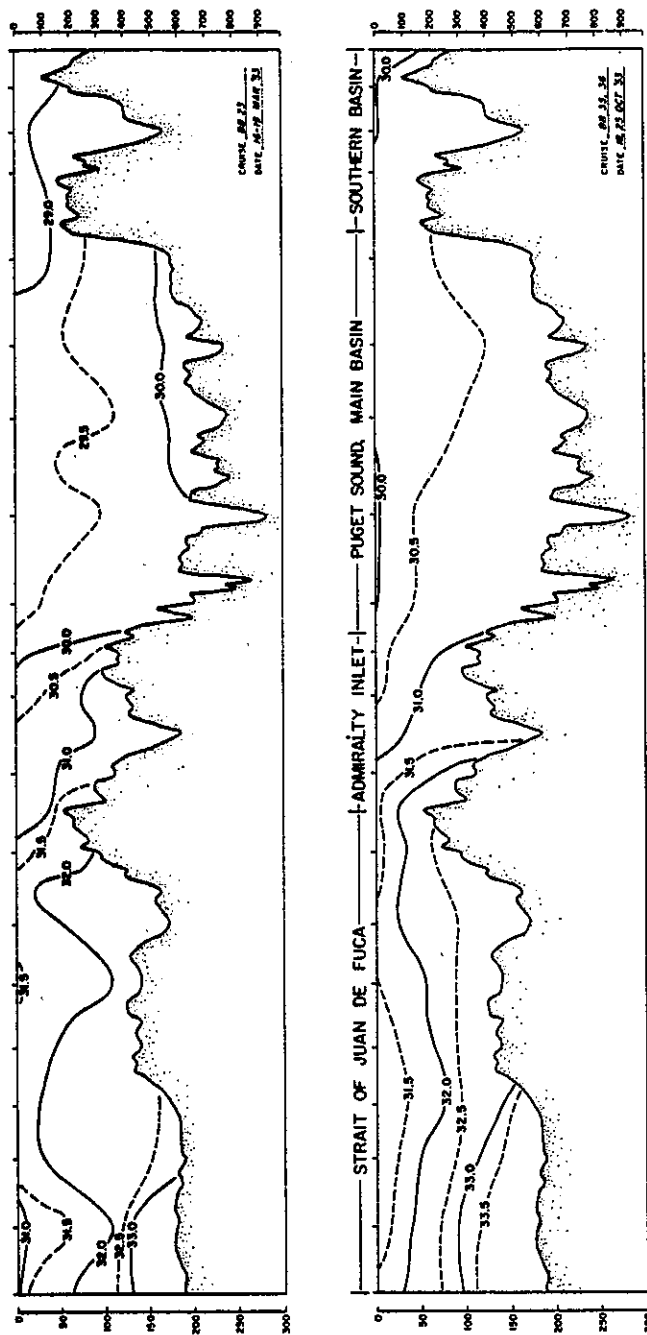
Figure III-4. Vertical Sections of Salinity (^{o}/oo) Through Puget Sound for March and October 1953.

Source: Collias et al., 1974.
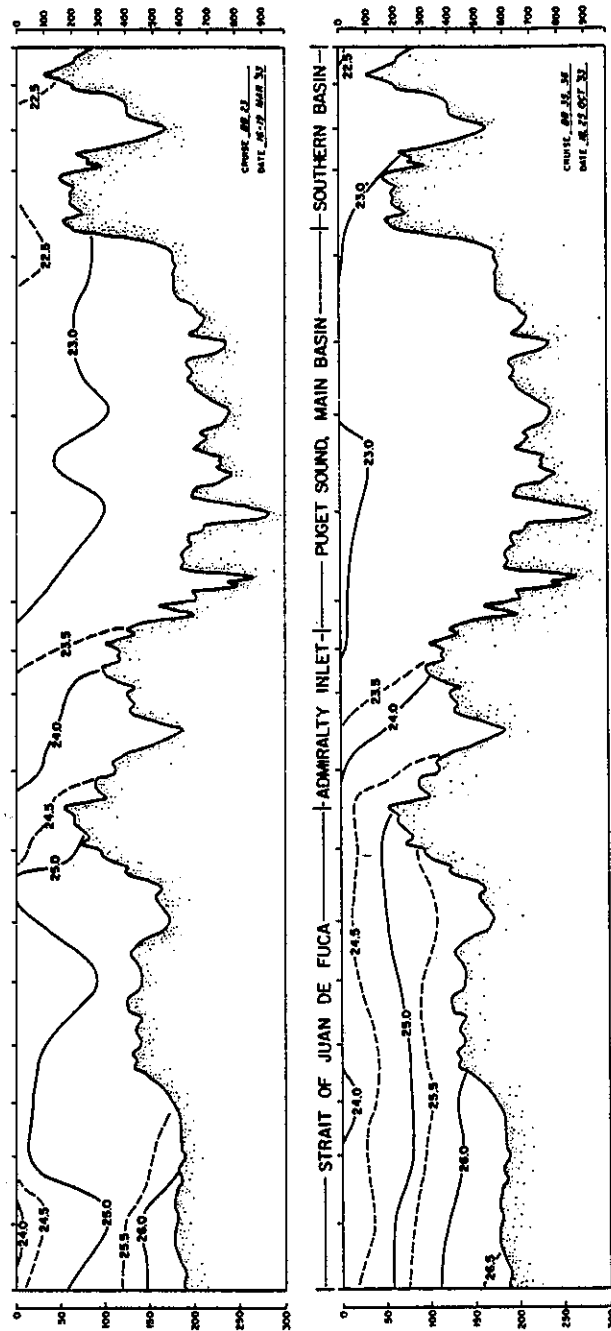
Figure III-5. Vertical Sections of Density (sigma-t) Through Puget Sound for March and October 1953.

Source: Collias et al., 1974.
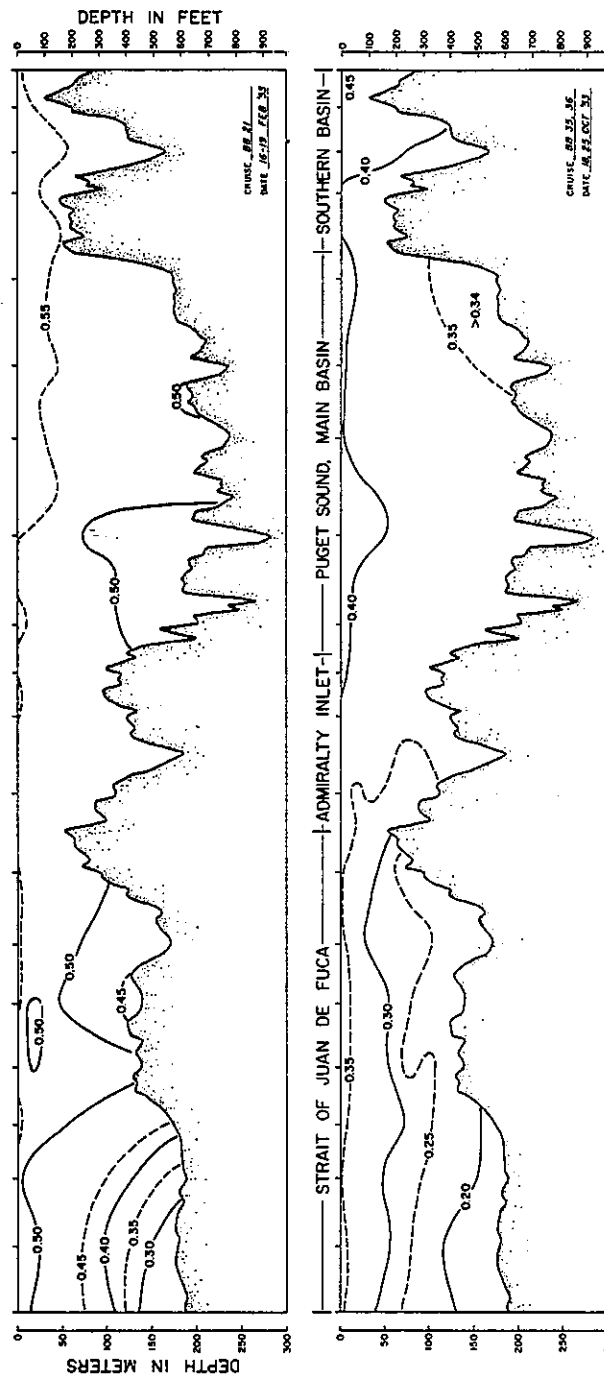
Figure III-6. Vertical Sections of Dissolved Oxygen (mg at/l) Through
Puget Sound for February and October 1953.

Source: Collias et al., 1974.

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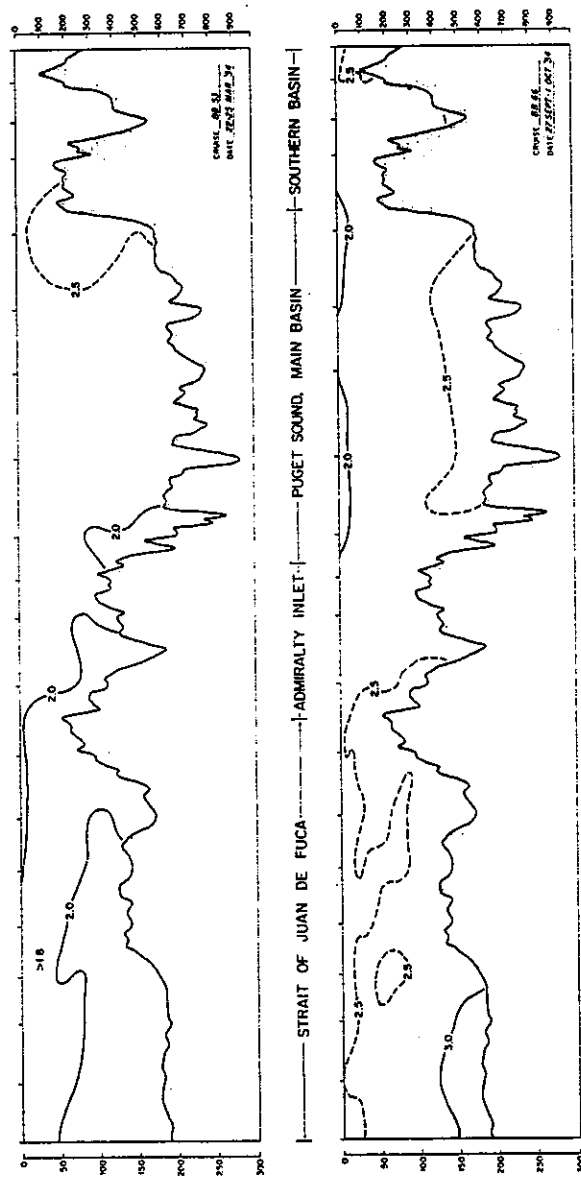
Figure III-7. Vertical Sections of Phosphate (μg –at /l) Through Puget Sound for March and October 1953.

Source: Collias et al., 1974.

CIRCULATION

Circulation in the Main Basin of Puget Sound responds to inputs of saltwater, freshwater, and heat. It is also controlled by tides, winds, and bathymetry, being significantly affected by constrictions. The general circulation in the Main Basin could be described as a two-layer system bounded to the north and south by sill areas (Admiralty Inlet and The Narrows) of intense mixing. The upper layer has a net northward (seaward) transport, while the deep layer moves southward (landward). Maximum landward transport occurs at a depth of approximately 100 m. The depth of no net motion is located at approximately 50 m. This depth can be changed significantly by runoff and winds.

Numerous studies have been conducted using a hydraulic tidal model of Puget Sound to investigate various aspects of Puget Sound circulation (Rattray and Lincoln, 1955). Patterns of surface currents observed in the model at eight stages of a typical tide were presented by McGary and Lincoln (1977). Model studies indicate that the net seaward transport in the upper layer is approximately proportional to the tidal prism landward of The Narrows.

The net landward transport has been estimated by Ebbesmeyer and Barnes (1980). Using dissolved oxygen as a timed tracer, mean current profiles were determined for various locations in the Main Basin. The net annual average landward transport in the lower layer estimated from these profiles was 2.7×10^4 m^3/sec. The bulk residence time for the lower layer, calculated as the lower layer volume divided by the transport, was 19 days.

Mixing Processes at Admiralty Inlet

Admiralty Inlet connects the Main Basin of Puget Sound with the Strait of Juan de Fuca. It is 32 km long and has outer and inner sills of 64 m and 104 m, respectively. Roughly 98 percent of the tidal prism for Puget Sound passes through this area. However, under usual conditions water on an ebb or flood tide does not transit all of Admiralty Inlet in one tidal cycle.

Refluxing of surface water. The simple picture of net seaward flow in the upper layer and net landward flow in the lower layer is complicated by mixing in Admiralty Inlet. A recent study indicates that a major portion of the upper layer is mixed downward and refluxed into the lower layer of the Main Basin rather than being advected into the Strait of Juan de Fuca (Ebbesmeyer and Barnes, 1980).

By examining temperature-salinity diagrams for stations just outside and inside of Admiralty Inlet, Ebbesmeyer and Barnes (1980) estimated that, on an annual average, the lower layer of the Main Basin was a mixture of 1/3 exterior (Strait of Juan de Fuca) water and 2/3 upper layer water.

The refluxing of upper layer water into the lower layer was also observed in the relationship between freshwater runoff and salinity at depth (100 m off Point Jefferson). Long-term mean monthly values of runoff, salinity, temperature, and density are shown by solid lines in Figure III-8. Deviations from these means, for the periods indicated, are denoted by the shaded areas. The long-term norms are based on mean monthly values for the period 1932-1975. A comparison of the long-term averages indicates that changes in salinity (ΔS) at depth are well correlated with changes in runoff (ΔR). The long-term average for $\Delta S/ \Delta R$ is equal to -7.6×10^{-4} o/oo $m^{-3}s$. Changes in salinity lag those in runoff by one to two months. Five periods of abnormal runoff and salinity are delineated by dashed lines spanned by arrows (Figure III-8). On the average, these abnormal periods exhibited the same relationship between changes in salinity and changes in runoff that was observed for the long-term comparison. This indicates that the relationship is most probably real and not just an artifact of the long-term averaging.

Ebbesmeyer and Barnes (1980) concluded that, based on the correspondence of these data, two-thirds of the runoff flowing seaward into Admiralty Inlet apparently is refluxed landward into the Main Basin's lower layer.

Bottom Water Replacement Processes. Historically, rapid replacement of bottom water was thought to occur in July through October in response to upwelling induced by northerly winds along the Pacific Coast (Barnes and Collias, 1958). This is the time of year when the most dense water occurs in the Strait of Juan de Fuca. Measurements of currents and water properties have since shown that bottom water replacement can occur at virtually any time of the year (Cannon and Ebbesmeyer, 1978; Cannon and Laird, 1978; Cannon, 1975; Cannon et al., 1979).

Bottom water is replaced by large intrusions of cold, saline water from the Strait of Juan de Fuca which transit Admiralty Inlet with very little mixing. Each intrusion has been observed to flow through Admiralty Inlet for about five days. Series of intrusions tended to occur at two-week intervals although intrusions did not occur every two weeks. At the present level of study, a complete understanding of the conditions under which intrusions occur has not been achieved. At least two important factors have been identified: 1) the tidal duration and range, and 2) the amount of freshwater in the surface layer.
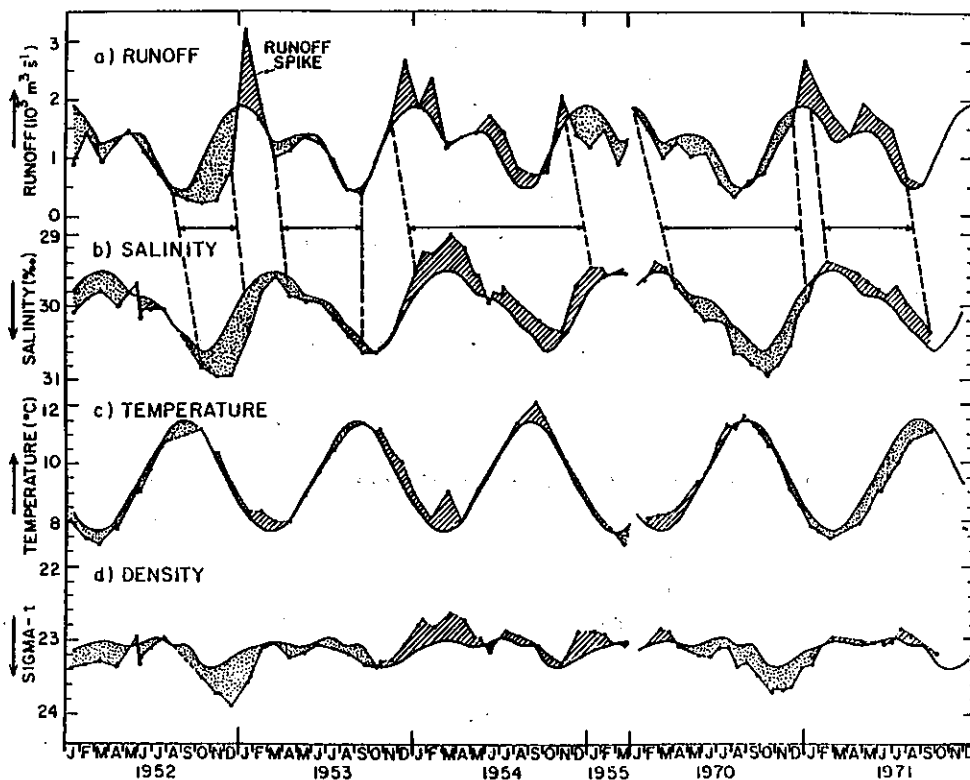
Figure III-8. Annual Cycles of (a) Runoff, (b) Salinity, (c) Temperature,
    and (d) Density. Solid lines are long-term averages. Dotted lines are
    actual values for periods indicated. Dashed lines spanned by
    arrows delineate abnormal periods of runoff.
Source: Ebbesmeyer and Barnes, 1980.

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Intrusions observed during the winter of 1973 and 1975 (Cannon and Ebbesmeyer, 1978; Cannon and Laird, 1978) were associated with large tidal ranges (>3.5 m at Seattle) coincident with clear weather and below freezing air temperatures. During the interval between intrusions the flow was tidal with a small net seaward component. It has been shown in the hydraulic tidal model that when tidal ranges are greater than 3.5 m (at Seattle) water can completely transit Admiralty Inlet in one tidal cycle (Farmer and Rattray, 1963) and would have little opportunity for mixing with the fresher upper layer. Thus, the occurrence of large tidal ranges was thought to be the mechanism responsible for producing intrusions.

However, further measurements showed that there were times of large tides when intrusions did not occur. Apparently, during much of the winter the influx of freshwater to the upper layer is sufficient that even during times of large flood tides when the extent of mixing is small, enough freshwater is mixed with the incoming bottom water to significantly decrease its density. Thus a bottom water intrusion would not be observed. The winter intrusions seen in 1973 and 1975 were characterized by large step decreases in the temperature of the incoming water. These intrusions followed cold periods of clear weather which reduced the amount of freshwater available for mixing.

Cannon et al. (1979) observed intrusions during periods of low tidal range and showed that the magnitude and duration of tidal currents as well as the tidal range could be important in determining when an intrusion would occur. They found that "during low tidal ranges new bottom water inflow was characterized by relatively lower maximum tidal currents, but for longer durations, than when no new bottom water was entering the Sound. Inflow during large tidal ranges showed both large durations and maximum currents" (Cannon et al., 1979, page 53). Research is continuing to more precisely define the conditions when intrusions occur.

It is not known how much water is actually replaced during any one intrusion. A bottom water replacement rate for major intrusions was calculated using daily average profiles of currents (Cannon and Ebbesmeyer, 1978). Currents were assumed constant across channel and the effects of diffusion and entrainment were assumed to be negligible. This replacement rate is defined as the lower layer volume divided by the lower layer transport. The rate applicable for all major intrusions was 9 days. Water property measurements showed that bottom water intrusions moved at an average speed of 8-to-10 cm/sec through the Main Basin (Cannon et al., 1979). This rate is consistent with the replacement rate discussed above.

Compensating outflows of surface water have been observed to accompany the inflows of bottom water. An example is shown in Figure III-9. These measurements were taken at a mooring located in mid-channel near the southern end of Admiralty Inlet. Increased outflow during intrusions also were observed at a mooring located at mid-channel near Seattle (Cannon et al., 1979).

Mixing Processes At The Narrows

The Narrows, a channel having a sill depth of 44 m, is located at Tacoma and is an area of intense mixing as indicated by vertically uniform water properties. Currents also are vertically uniform and are proportional to the tide height. Within The Narrows, ebb currents are stronger on the east side while flood currents are stronger on the west side. This condition, which has been presented in tidal current tables and seen in the hydraulic tidal model (McGary and Lincoln, 1977), is attributed to bathymetric effects.

All of the tidal prism for the Southern Sound must pass through The Narrows, which acts as a tidal pump exchanging water between the Main Basin and Southern Sound. On flood tide, deep East Passage water upwells at The Narrows. A stratified mixture of deep and surface water enters The Narrows, is thoroughly mixed, and exits into the Southern Sound. On ebb tide some of this mixture along with some Southern Sound water returns through The Narrows. This new mixture also is mixed thoroughly in The Narrows and exits through Colvos Passage, reentering the Main Basin near Alki Point. Some of the water recirculates southward around Vashon Island while some moves seaward in the upper layer of the Main Basin (Barnes and Ebbesmeyer, 1978).

Tidal pumping thus produces a net clockwise circulation around Vashon Island (Figure III-10). Colvos Passage has dominant ebb currents and very weak flood currents, producing a net flow to the north at all depths. Flood currents dominate in East Passage producing a net southerly flow at all depths. The flow regime found in most of Puget Sound (net seaward surface flow and net landward deep flow) is not present in these two channels. The resulting clockwise circulation around Vashon Island has been observed in the hydraulic tidal model of Puget Sound (Farmer and Rattray, 1963) and in the field (Cannon et al., 1979).

Cannon et al. (1979) observed incidences of upwelling of East Passage water occurring during both flood and ebb tides. Previously, it had been thought that this upwelling occurred only on flood tides. Upwelling of East Passage water during an ebb tide may be caused by the northward flow of water into Colvos Passage. These ebb tide flow reversals to the south in East Passage occurred when currents in Colvos Passage were strong and may be dependent on a "threshold velocity" in Colvos Passage (Cannon et al., 1979).
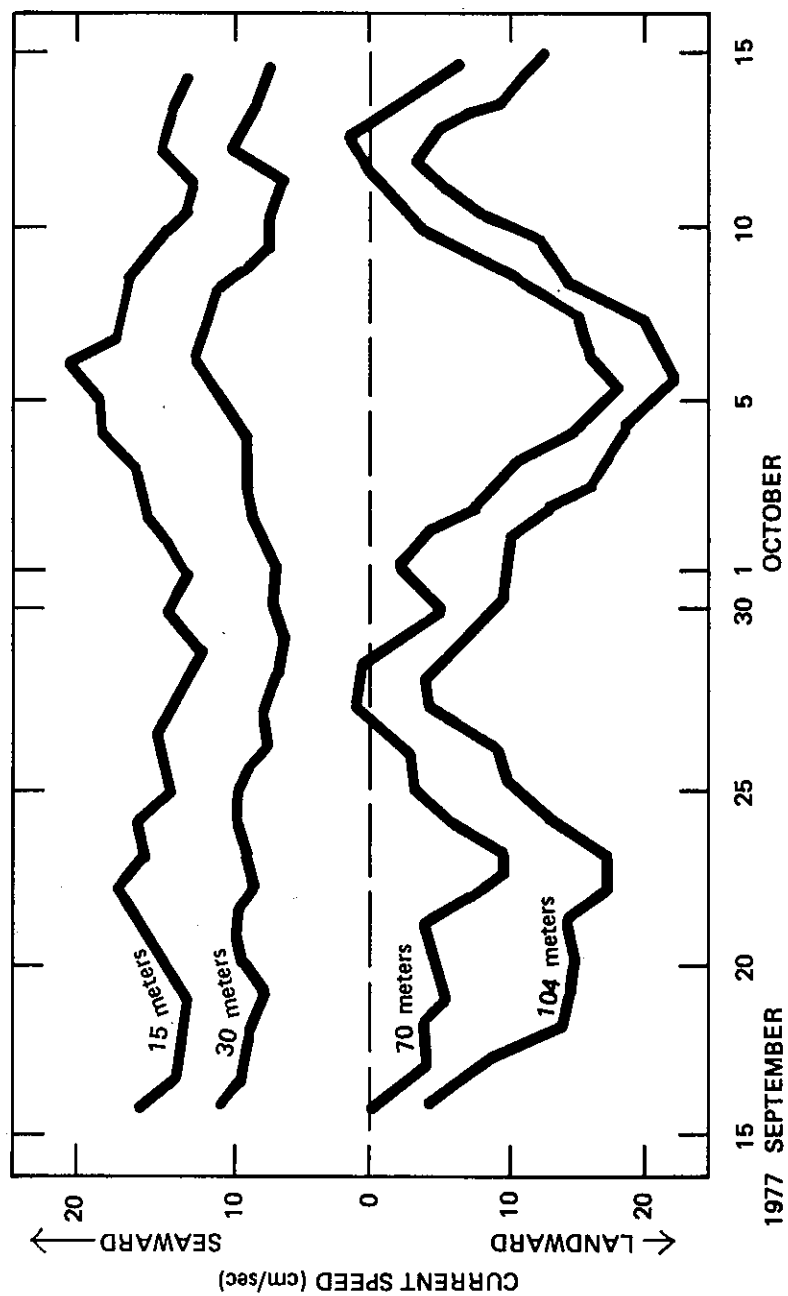
Figure III-9. Daily Average Along Channel Currents at Four Depths in Admiralty Inlet.

Source: Cannon et al., 1979.
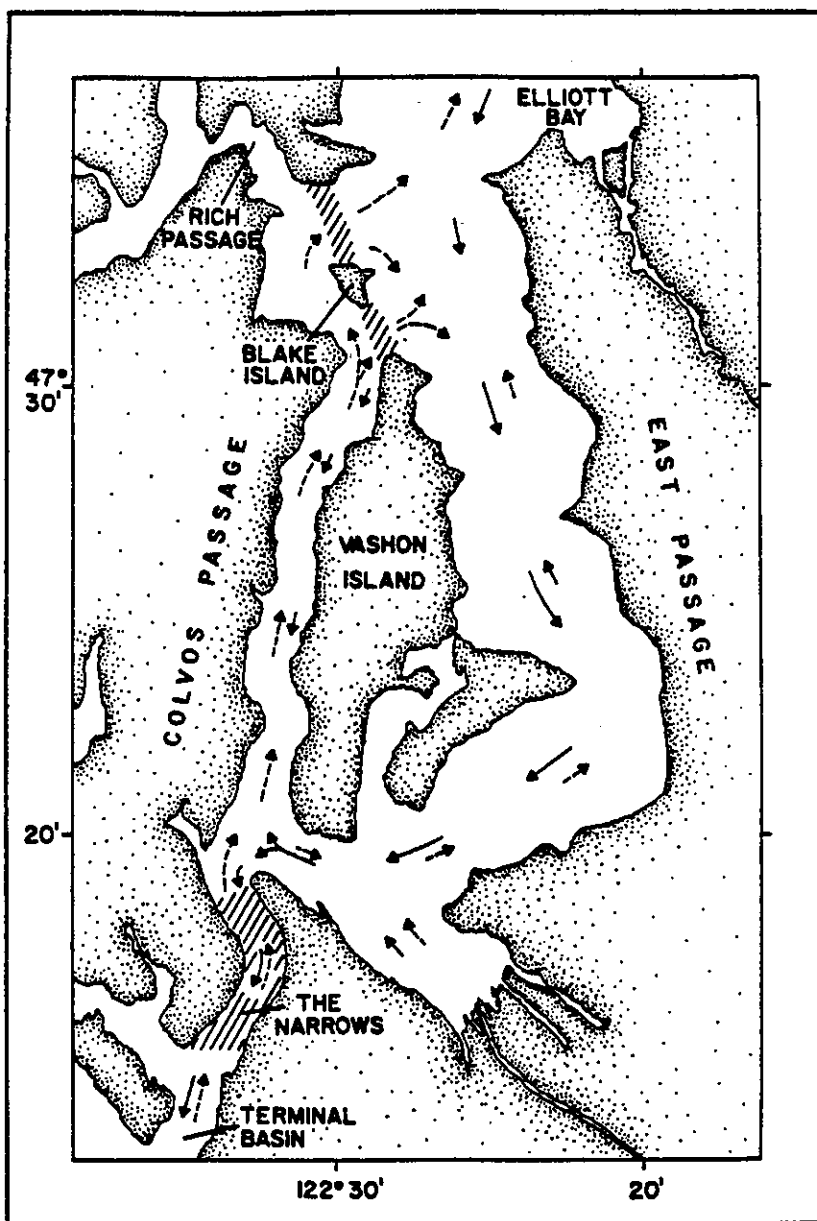
Figure III-10. Circulation Around Vashon Island. Solid lines are flood
currents. Dashed lines are ebb currents. Relative length of line
corresponds to strength of current.

Source: Helseth et al., 1979.

The tidal pumping at The Narrows appears to be the major factor responsible for the large transport in the Main Basin according to studies conducted by Barnes and Ebbesmeyer (1978) using the hydraulic tidal model of Puget Sound. A complete blockage of The Narrows greatly slowed circulation in the Main Basin, and produced a reversal of the mean surface currents in East Passage resulting in net seaward surface currents. A complete blockage of Colvos Passage (leaving The Narrows open) also resulted in a current reversal in East Passage and circulation in the Main Basin was slowed, but not as greatly as with the blocking of The Narrows.

Horizontal Mixing

Tidal eddies have been frequently observed in the hydraulic tidal model (McGary and Lincoln, 1977). The eddies move water horizontally in Puget Sound and promote horizontal mixing and dispersion. Drogue and dye studies conducted in the upper 70 m near West Point (Ebbesmeyer and Helseth, 1975; Bendiner, 1976) yielded results demonstrating the same major flow characteristics observed in the model.

Results showed that during established tidal phases eddies were well developed. During slack water the large eddies were broken down into many smaller eddies resulting in a faster mixing rate during slack tides. Eddies which developed during a flood or ebb tide were not always completely broken down during the next slack water. Some drogue patches maintained their identity for up to 15 hours while it required at least two current reversals to dilute some dye patches below detectable concentrations.

Wind Effects

Winds over Puget Sound - predominantly from the south in the fall, winter, and spring and predominantly from the north in the summer - directly affect the surface waters of Puget Sound and indirectly affect upper and lower layer circulation. Direct effects include wind waves and surface currents induced by wind stress. Harris and Rattray (1954) calculated that average winds in both winter and summer produced average surface currents of 0.2 m/sec. Sustained high velocity winds could produce surface currents up to 0.5 m/sec. These are comparable with the average maximum ebb and flood currents measured in Puget Sound away from major constrictions, which range from 0.05 to 0.8 m/sec (Table II-1).

The maximum height a wind wave can achieve is dependent on the wind speed and duration, and fetch length. Fetches are relatively short in Puget Sound, the longer ones being 63 km through the Main Basin and 52 km through Admiralty Inlet. Harris and Rattray (1954) reviewed a three-year wind record for Puget Sound. Maximum sustained winds of

30 to 42 km/hr occurred on several occasions, with a maximum duration of six to eight hours. Harris and Rattray (1954) calculated that maximum wave heights of two to three meters could be attained from such winds. No direct studies have been made.

Southerly winds enhance the movement of the seaward flowing upper layer while northerly winds retard the movement of this layer. A change in the winds from southerly to northerly retards the seaward flow of water which results in deepening the level of no net motion. The depth can change significantly, increasing from 50 m to 100 m at times. A return to quasi-steady winds resulted in the level of no net motion returning to its previous position (Cannon et al., 1979).

Circulation Summary

. The general circulation in the Main Basin can be described as a two-layer system with net seaward flow in the upper layer and net landward flow in the lower layer. The average bulk residence time for the lower layer, calculated as the lower layer volume divided by the transport is 19 days.

In Admiralty Inlet a major portion of the seaward flowing surface layer is mixed downward into the lower layer and is refluxed into the Main Basin. The lower layer is estimated to be a mixture of one-third exterior water and two-thirds upper layer water on an annual average basis.

Tidal pumping in The Narrows produces a net clockwise circulation pattern around Vashon Island. Deep East Passage water is upwelled on flood tide, but can also be upwelled on ebb tides. The occurrence of an ebb tide flow reversal to the south in East Passage might be dependent upon a threshold velocity in Colvos Passage. Tidal pumping in The Narrows is a major factor responsible for the large transport in the Main Basin.

This relatively simple model of cycling between The Narrows and Admiralty Inlet is complicated by a periodic and rapid replacement of deep water in the Sound by intrusions of undiluted water from the Strait of Juan de Fuca.

When a series of bottom water intrusions occur, the intrusions tend to be spaced at two week intervals. These intrusions can apparently occur any time of the year in response to flood currents of long duration and/or large tidal range. An abundance of freshwater in the upper layer may prevent an intrusion from occurring by mixing with the incoming water thereby significantly reducing the density of the mixture. It is not known how much deep water is actually replaced during any one intrusion. The replacement rate calculated for major intrusions was nine days.

ELLIOTT BAY

Elliott Bay is located about midway along the length and on the east side of the Main Basin. The Port of Seattle is situated on Elliott Bay. A deep channel extends from the Main Basin into Elliott Bay and separates into two channels around the Duwamish River delta (Figure III-11).

DUWAMISH RIVER ESTUARY

The Duwamish River discharges into Elliott Bay on both the east and west side of Harbor Island. Most of the water flows through the West Waterway. The Duwamish River receives most of its water from the Green River. The Black River joins the Green River to form the Duwamish at river kilometer (km) 19. Tidal fluctuations are observed at the mouth of the Black River so the Duwamish is considered to be tidal over its entire length. The lower 8 km of the Duwamish River has been considerably modified over the years to improve navigation. The channel has been straightened and is presently maintained by dredging to depths of from 3 m (river km 5) to 9 m at the mouth. The Duwamish River estuary is primarily a salt-wedge estuary with the toe of the wedge frequently near river km 12. Most of the information on the Duwamish River estuary presented in this section is summarized from Santos and Stoner (1972).

Freshwater Input

The Duwamish River has a present drainage basin of 483 square miles. More than 90 percent of this basin is drained by the Green River. Streamflow data is collected at two gaging stations, one at Auburn and one at Tukwila. The mean monthly and minimum monthly discharges measured at Auburn for the period 1937-1965 are shown in Figure III-12. The minimum, maximum and average annual discharges for this period were 1120 m^3/min, 3024 m^3/min and 2295 m^3/min, respectively.

Tides

The tides at river km 6.9 have mean and diurnal ranges of 2.3 m and 3.4 m, respectively. The mean tide level at this location is 2.0 m (NOS, 1980a). Predicted tide stages agree well with measured tides. Recorded tides have ranged from minus 1.4 m to plus 4.5 m.

Estuary Circulation

The Duwamish River estuary is usually a classical salt-wedge estuary but during low river discharge it is a partially mixed estuary. Stratification is strong when the discharge is high and becomes less
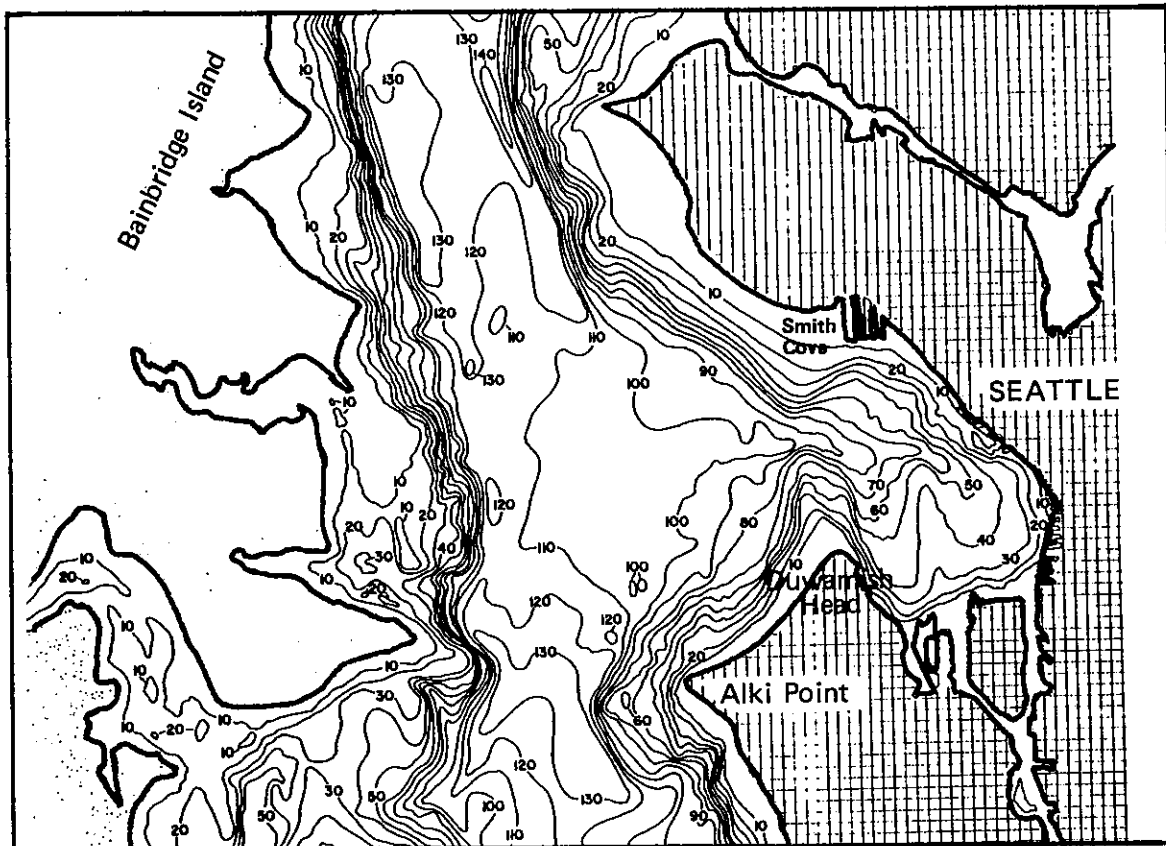
Figure III-11. Bathymetry (Fathoms) of Elliott Bay and Approaches.
Source: Hinchey et al., 1980.
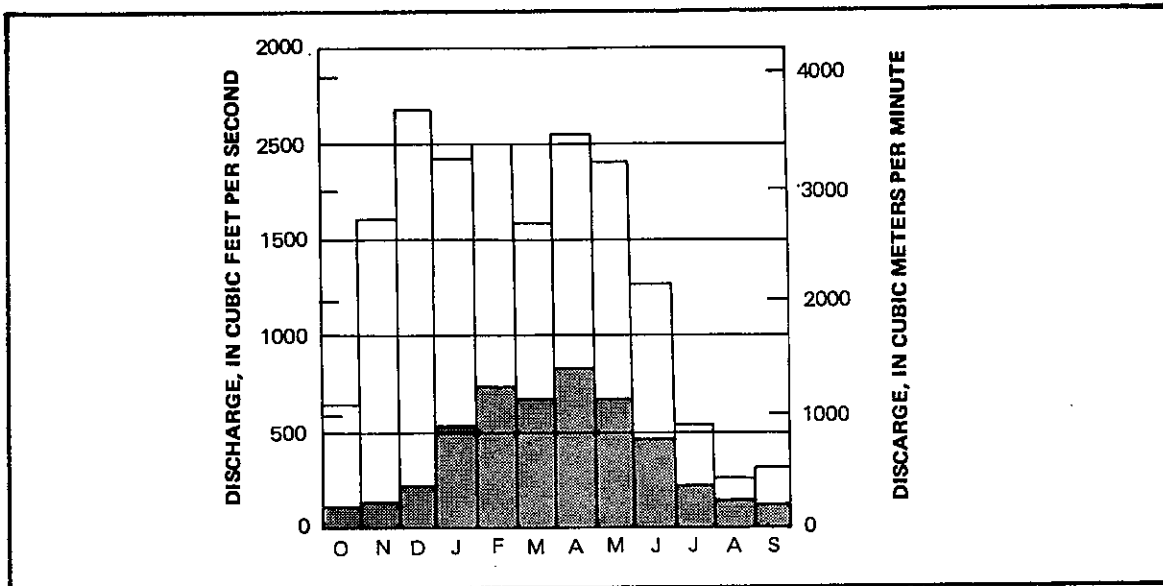
Figure III-12. Mean Monthly and Minimum Monthly Discharges of the Green
River near Auburn. Based on the 29-year period, 1937-1965.

Source: Santos and Stoner, 1972.

well defined as the discharge decreases. Upstream of km 5.6 the estuary is always a salt-wedge; or, in the Hansen-Rattray classification system (Hansen and Rattray, 1966), a type 4 estuary. This classification is representative of the whole estuary when the discharge is greater than 1700 m^3/min. For discharges less than 1700 m^3/min, the estuary grades into a partially mixed or type 2B downstream of km 5.6 as diffusion and advection act to reduce the stratification.

Circulation in the estuary follows the patterns described by Pritchard (1955) for a salt-wedge estuary. Net motion in the bottom layer is upstream driven by entrainment into the downstream flowing fresher surface layer. Dye studies indicate that virtually no down-mixing occurs. For this reason any pollutants carried by the river would remain in the surface layer through the estuary. The surface layer thickness is approximately 1.5 m to 5 m, increasing with greater discharge.

The extent of saltwater intrusion is shown by the distribution of salinity in the estuary and depends on tidal conditions and freshwater discharge. Salinity increases as discharge decreases. The estuary is very narrow compared to its length and, in general, salinity is laterally uniform. The upstream extent of saltwater intrusion depends on river discharge and tide height. Stoner (1967) showed that at river km 21 (Renton Junction) the water was always fresh. At river km 12.6 (East Marginal Way), when the discharge was >1700 m^3/min there was no saltwater intrusion regardless of tide height. When the discharge is <1108 m^3/min there was always saltwater in the bottom layer. Between these limits the occurrence of saltwater intrusion increased with tidal height.

Flushing

Based on dye studies, the flushing time of the Duwamish River Estuary (time required for a parcel of water to move from river km 21 to the mouth) was at least seven days during low flow. Flushing time was strongly dependent on freshwater discharge; as the discharge increases, the flushing time decreases.

Distribution of Duwamish Water Properties

Dissolved oxygen (DO) data have been collected by several different agencies at various times since 1948. In general the data indicate that DO concentrations in the upper freshwater layer decrease in a downstream direction. DO concentrations in the lower saltwater layer decrease in an upstream direction. Minimum DO concentrations occur between river km 7.7 and river km 10.4 (in the lower layer). Lowest concentrations are associated with low river discharge and small tidal exchange. Figure III-13
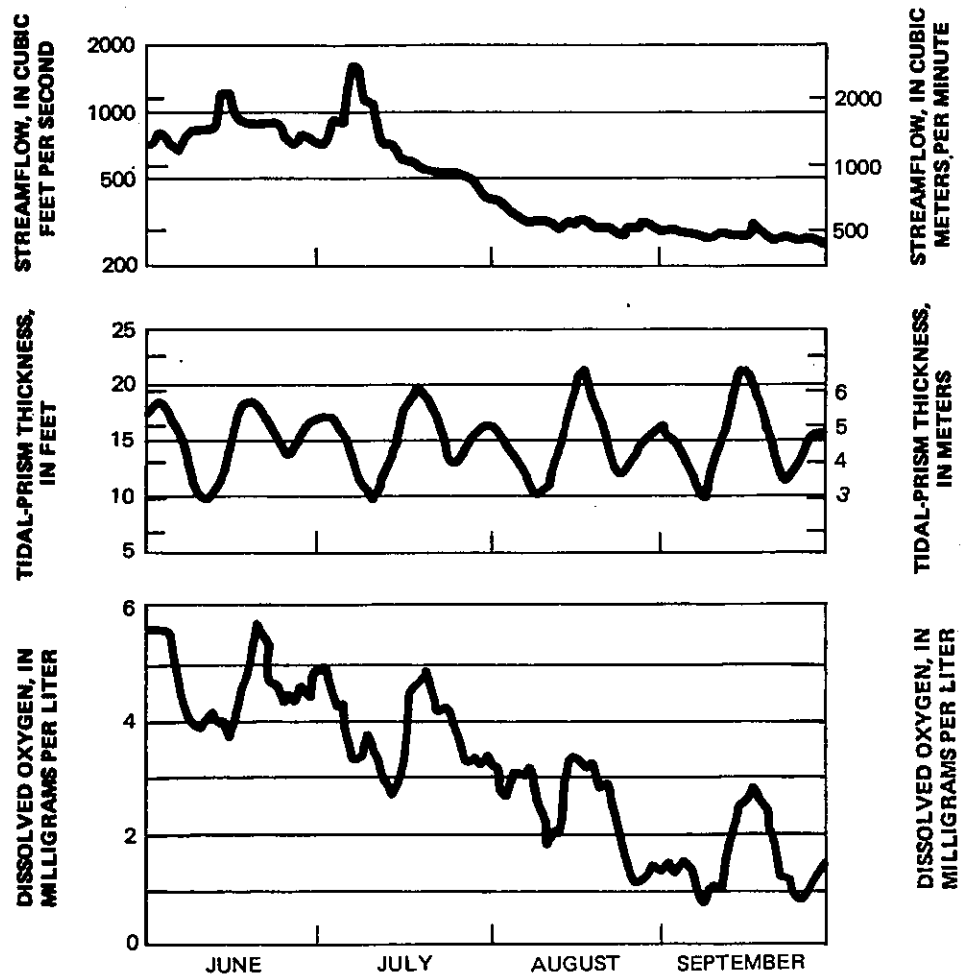
Figure III-13. Mean Daily Freshwater Inflow, Tidal-Prism Thickness and Minimum Bottom DO at River km 7.7, June through September 1966.

Source: Santos and Stoner, 1972.

shows the decline in DO with decreasing streamflow and tidal-prism thickness during summer.

DISTRIBUTION OF WATER PROPERTIES IN ELLIOTT BAY

Data from 50 m at four Metro stations in Elliott Bay have been averaged to obtain annual cycles of temperature, salinity, density and DO in the bay (Figure III-14). Annual cycles of salinity, temperature, density and DO in Elliott Bay follow the general patterns of these properties in the Main Basin (Figure III-2).

Surface temperatures are nearly identical in the Main Basin and Elliott Bay. The surface water in the bay is fresher and less dense than that in the Main Basin, showing the effects of the Duwamish River. Dissolved oxygen at depth is virtually the same in the two regions. At the surface, DO concentrations are generally lower in Elliott Bay.

Surface salinities in Elliott Bay generally decrease from west to east suggesting that the Duwamish River tends to flow along the east side of the bay. Figure III-15 shows a distribution of surface water salinities taken over several tidal cycles.

CIRCULATION IN ELLIOTT BAY

A study of Elliott Bay circulation was conducted by Winter (1977) using dye injected into the hydraulic tidal model. He found that on flood tides the surface circulation was clockwise. On ebb tides the flow reversed directions and flowed counterclockwise with water exiting past Smith Cove. The net motion was clockwise, with surface water flowing out of the bay around Duwamish Head, especially during periods of low river discharge and spring tides. Only during periods of high river discharge and low tidal currents was a net counterclockwise current observed.

Distributions of water properties seem to be in disagreement with a clockwise surface circulation pattern. Surface salinities and temperatures taken over several years by different investigators indicate that the water in the bay moves east and north along the Seattle waterfront and exits into the Main Basin past Smith Cove. Photographs of suspended sediment from the Duwamish River plume show the same counterclockwise circulation pattern (Hinchey et al., 1980).

This counterclockwise pattern is thought to be due to local wind effects which are not included in the hydraulic tidal model. Regional winds are from the north during summer and from the south from
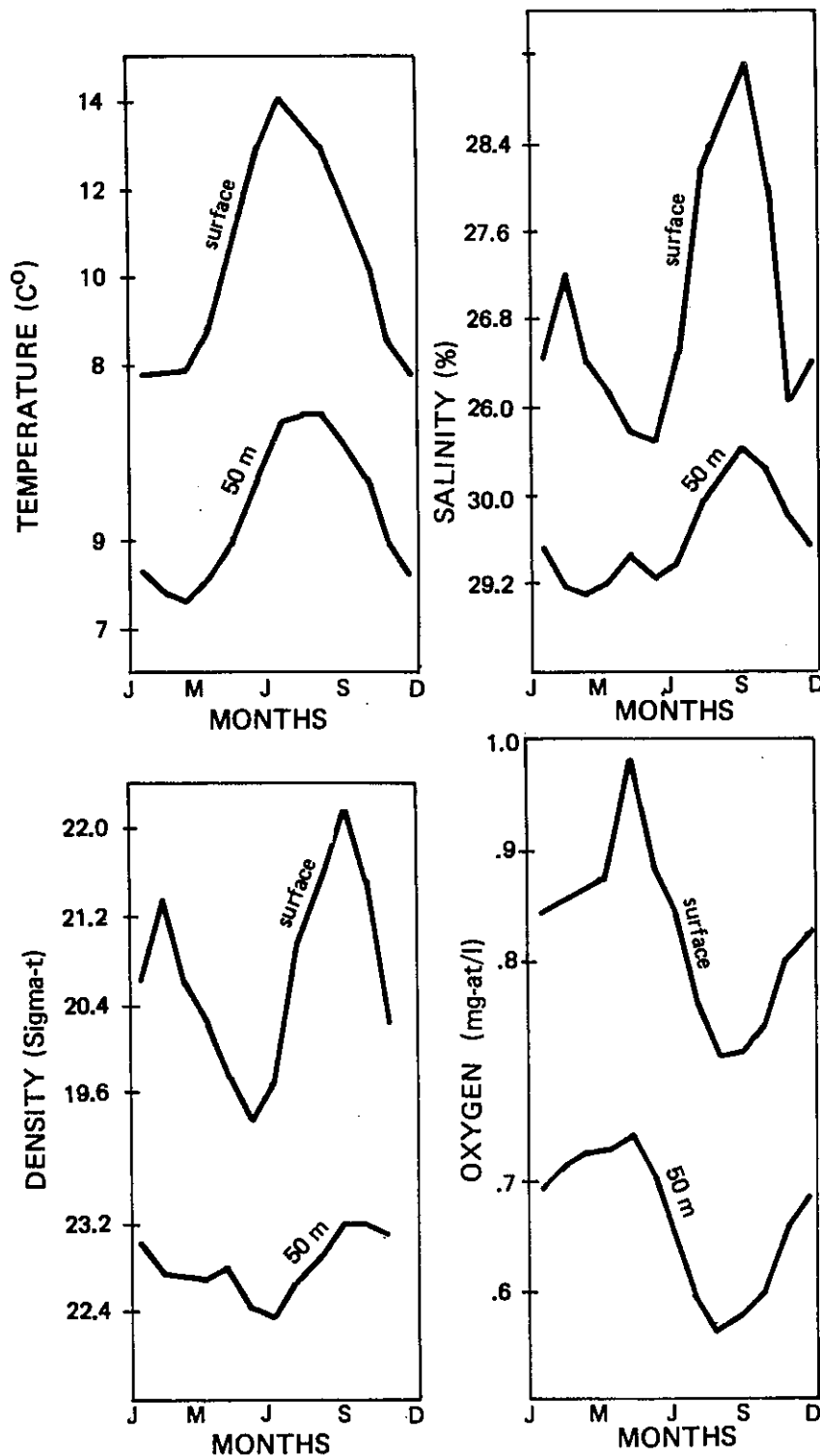
Figure III-14. Annual Cycles of Temperature, Salinity, Density, and Dissolved Oxygen at the Surface and 50 m Depths. Data collected from 1966 to 1980 were averaged from four METRO Elliott Bay Stations.

Source: Hinchey et al., 1980.
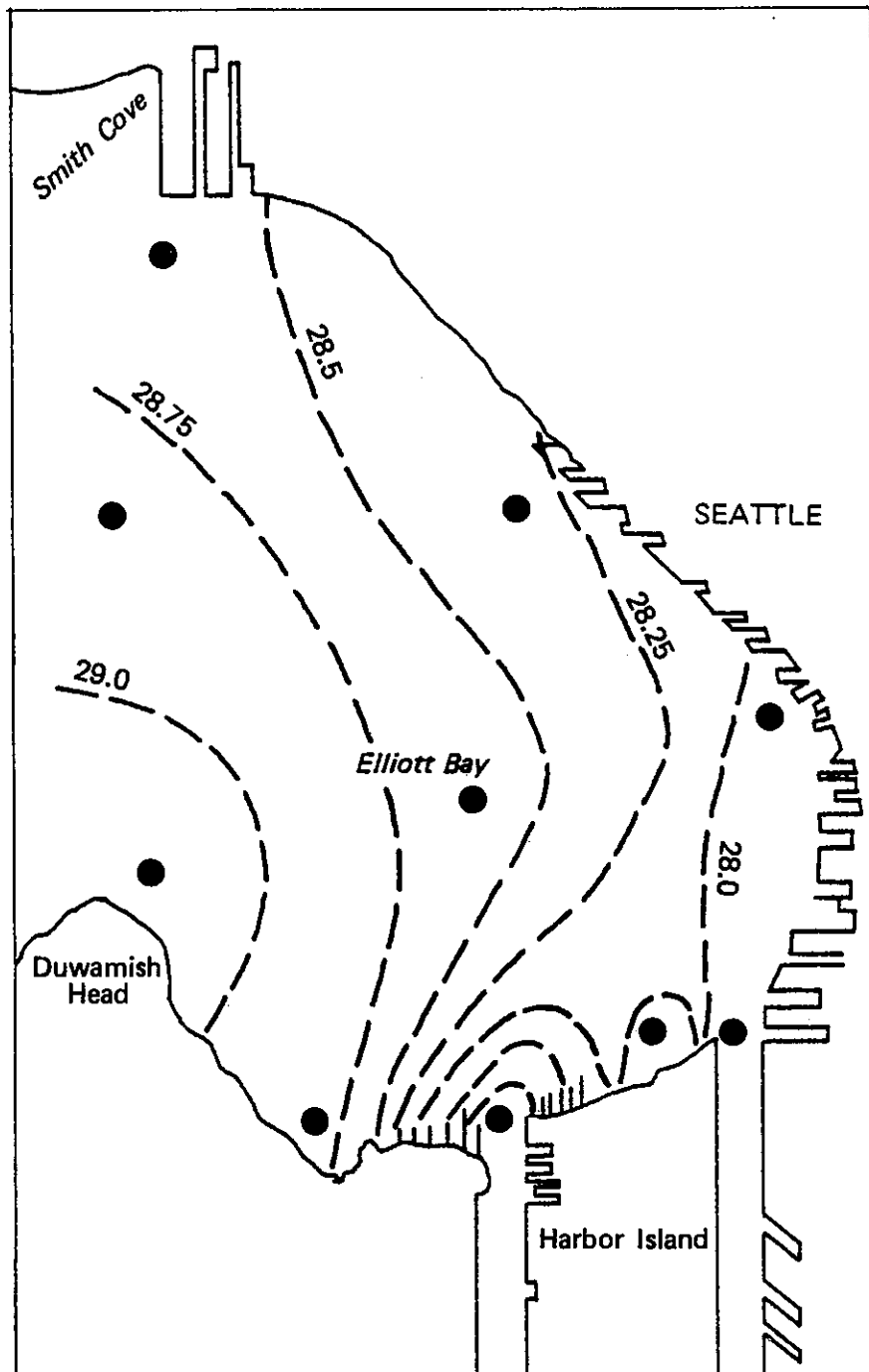
Figure III-15. Surface Salinity Distribution in Elliott Bay During September 24-27, 1974.

Source: Hinchey et al., 1980.

fall through spring. However, these winds are greatly affected by the local topography of the Seattle area (Figure III-16). Data recorded at the Seattle Center indicate a sea breeze effect and show that during the afternoons there is a significant onshore breeze. This onshore breeze pushes water toward the eastern part of the bay. Wind records at Harbor Island show that 45 percent of the winds annually are from the south. These winds would push water northward out of the bay. These two patterns combined with the shape of the shoreline produce a counter-clockwise circulation pattern in the surface waters (Hinchey et al., 1980).

Deep water circulation also has been studied in the hydraulic tidal model. Deep water from the Main Basin upwelled through the constriction (Figure III-11) at the mouth of Elliott Bay. This water rose to approximately 37 meters where it began to be incorporated into the surface flow (Winter, 1977). This upwelling process has not been documented by field observations.

FLUSHING

Dye studies conducted by Winter (1977) showed that dye injected into the model could have residence times of up to 3.5 days at times when the flow was north along the east side of the bay. Net annual current speeds calculated from DO data are 1.3 cm/sec and 0.6 cm/sec for water at 25 and 50 m, respectively. These figures yield residence times of 5-10 days (Hinchey et al., 1980). Actual current meter data yielded a net speed of 2 cm/sec thereby reducing the residence time almost by half (Hinchey et al., 1980). Depending on the exact tidal, wind and discharge conditions flushing times in Elliott Bay can apparently range from 2 to 10 days.
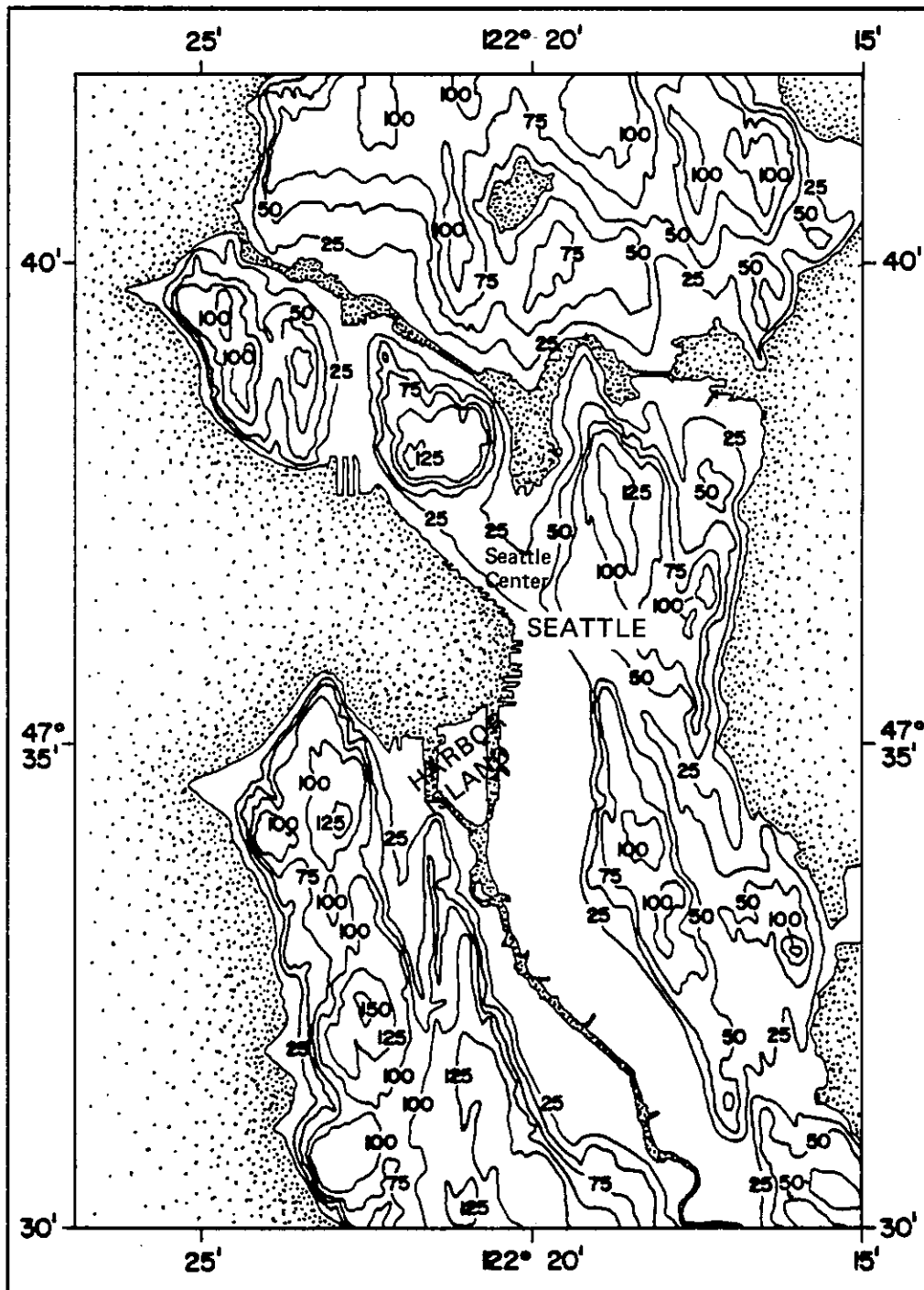
Figure III-16. Topography in the Vicinity of Elliott Bay (meters).

Source: Hinchey et al., 1980.

COMMENCEMENT BAY

An area map of Commencement Bay and approaches is presented in Figure III-17.

SALINITY DISTRIBUTION

Surface salinities in Commencement Bay range from 14°/oo to 26°/oo reflecting the input of Puyallup River water. Salinity distributions show that during calm or light winds the river water moves north toward Brown's Point on flood tides. During strong northerly wind the river water can be detected along the southwestern shore (Brown and Caldwell, 1957). Vertical salinity profiles show that the fresher surface layer is 1 m to 3 m thick.

CIRCULATION

Although several short-term circulation studies have been conducted in Commencement Bay, no long-term studies have been conducted there. Short-term studies realistically only can describe conditions at the time and location of sampling since the driving mechanisms cannot be well defined. Without knowing to what degree the conditions prevalent during the study are representative of conditions at other times, extrapolation of results to other times cannot be adequately justified.

Valuable information has been gained from the studies conducted in Commencement Bay. However, the above caution should be kept in mind when interpreting results.

Surface Water Circulation

Circulation studies have been done using drogues, aerial photographs, and the hydraulic tidal model. Based on drogue studies, Orlob et al. (1950) found that surface water moved out of the bay on both flood and ebb tides. In the inner bay water moved faster on ebb tides whereas in the outer bay the water moved faster on flood tide. This occurred because on an ebb tide the river flow and tidal currents act together to move water out of the inner bay and the force of the river flow diminishes with distance from the mouth. On a flood tide the river flow and tidal current act in opposite directions in the inner part of the bay, whereas in the outer part the surface flow is drawn into the flow moving through Dalco Passage into The Narrows.
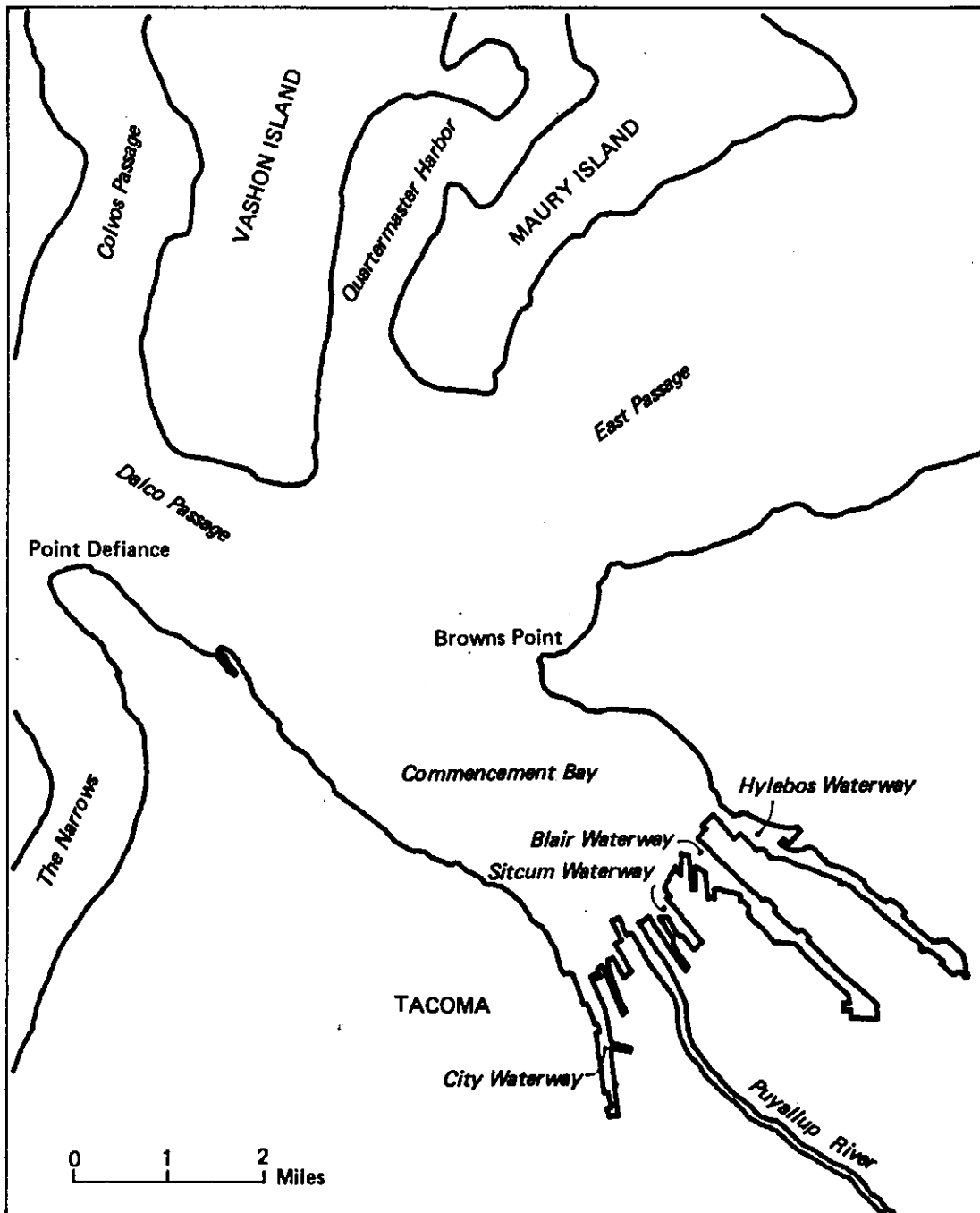
Figure III-17. Area Map of Commencement Bay and Approaches.

Aerial photographs of the river plume and salinity measurements showed that the surface flow was greatly affected by winds. During light winds the surface flow seemed to favor the northeast side of Commencement Bay. Photographs also show that silt clouds can extend north to Des Moines on an ebb tide. During flood tides the plume can enter Quartermaster Harbor (Brown and Caldwell, 1957).

Dye injected into the hydraulic tidal model showed that Puyallup River water was released in pulses during ebb tides. The river water then disperses, moving toward Brown's Point. Moving through Dalco Passage the surface layer enters The Narrows where it is mixed thoroughly with surrounding waters (Brown and Caldwell, 1957).

Deep Water Circulation

Tyler (1950) used salinity to trace the deep water circulation in Commencement Bay. Brown and Caldwell (1957) also traced deep water circulation using drogues at 30 m and 60 m. The results of both studies were similar and showed that on flood tides deep water flows to the southwest into the bay. As it approached the southwest shoreline the flow split, establishing currents toward Point Defiance and into Commencement Bay. The flow into the bay continued in a counterclockwise direction flowing out past Brown's Point. During ebb tides this flow pattern was disrupted but the net flow seemed to be counterclockwise. Drogues at 60m had average speeds of 10 cm/sec.

SINCLAIR INLET AND THE PORT ORCHARD SYSTEM

The Port Orchard system is made up of several channels and inlets and is located west of Bainbridge Island. It connects to the Main Basin of Puget Sound via Agate Passage and Rich Passage. An area map of the Port Orchard system is presented in Figure III-18.

DISTRIBUTION OF WATER PROPERTIES

Water property data including salinity, temperature, density, dissolved oxygen, phosphate, silicate, nitrate, nitrite and ammonia were collected throughout the Port Orchard system at three week intervals during the summer of 1975. Vertical distributions for some of these properties are shown in Figures III-19 through III-23 (Lincoln and Collias, 1975).

The water in the upper 50 m was denser in the southern part of the system than in the northern part. The reverse was true for deep water. The dissolved oxygen (DO) distribution followed a pattern similar to density with higher DO values observed in areas of lower density. Data collected from April through August showed that DO values within the system were greater than 0.5 mg-at/l. Deep water values off Manchester and in Port Madison were below this level in July and August.

During the summer, the nutrients, phosphate, silicate, nitrate and nitrite, generally had higher concentrations in the southern part of the system. Rich Passage had higher levels than Agate Passage, and Sinclair Inlet had higher levels than Liberty Bay.

Water property data for the entire Port Orchard system have not been collected at other times of the year.

CIRCULATION

Within the Port Orchard system, currents are strong only in the narrow channels of Agate Passage, Rich Passage and the Port Washington Narrows. Maximum average flood and ebb currents for these passages are listed in Table III-1 and are shown in Figure III-24. According to the Tidal Current Tables (NOS, 1980b) currents in Sinclair Inlet, Liberty Bay, Port Orchard, and Port Madison are too weak and variable to be predicted.
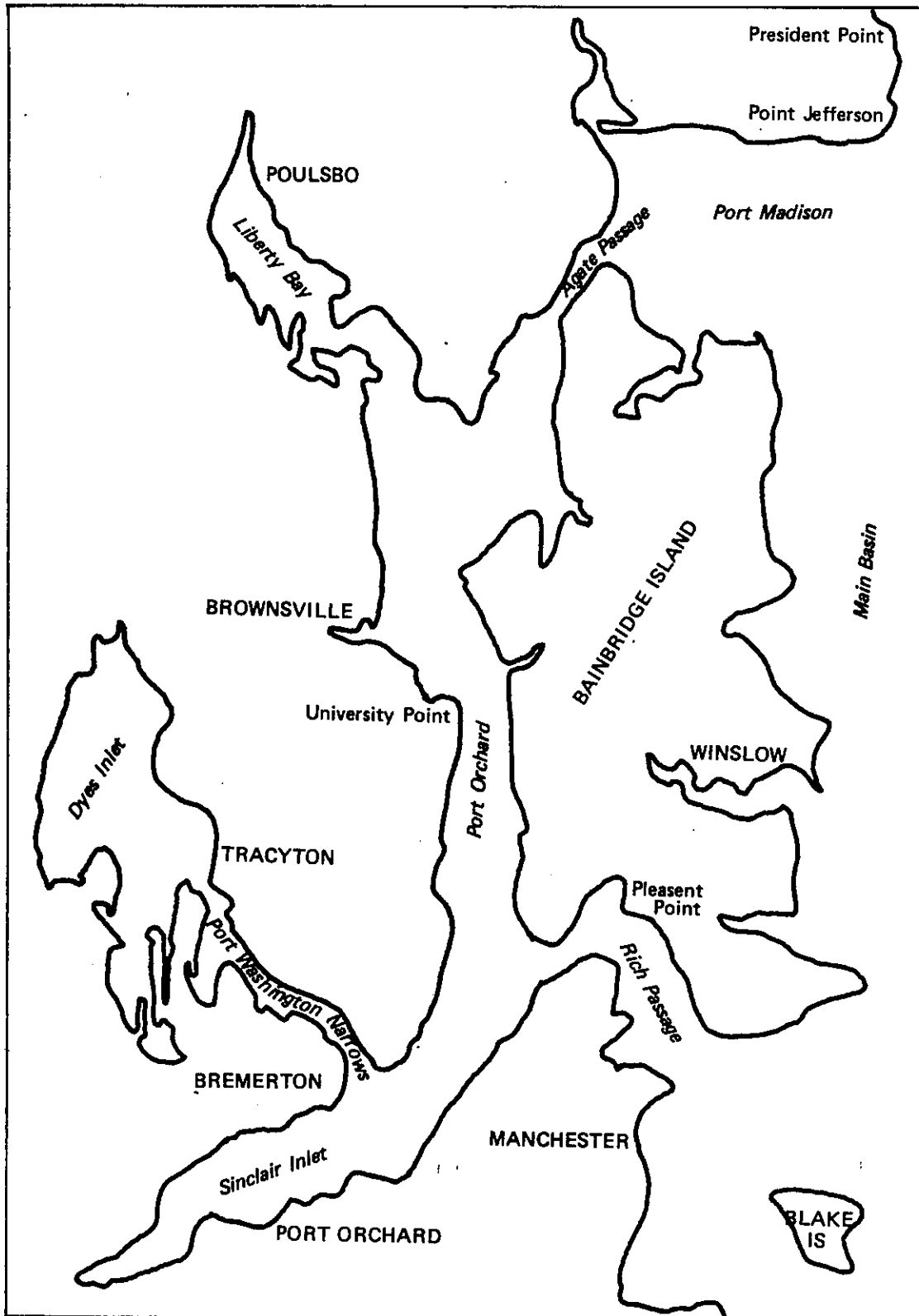
Figure III-18.   Area Map of the Port Orchard System.
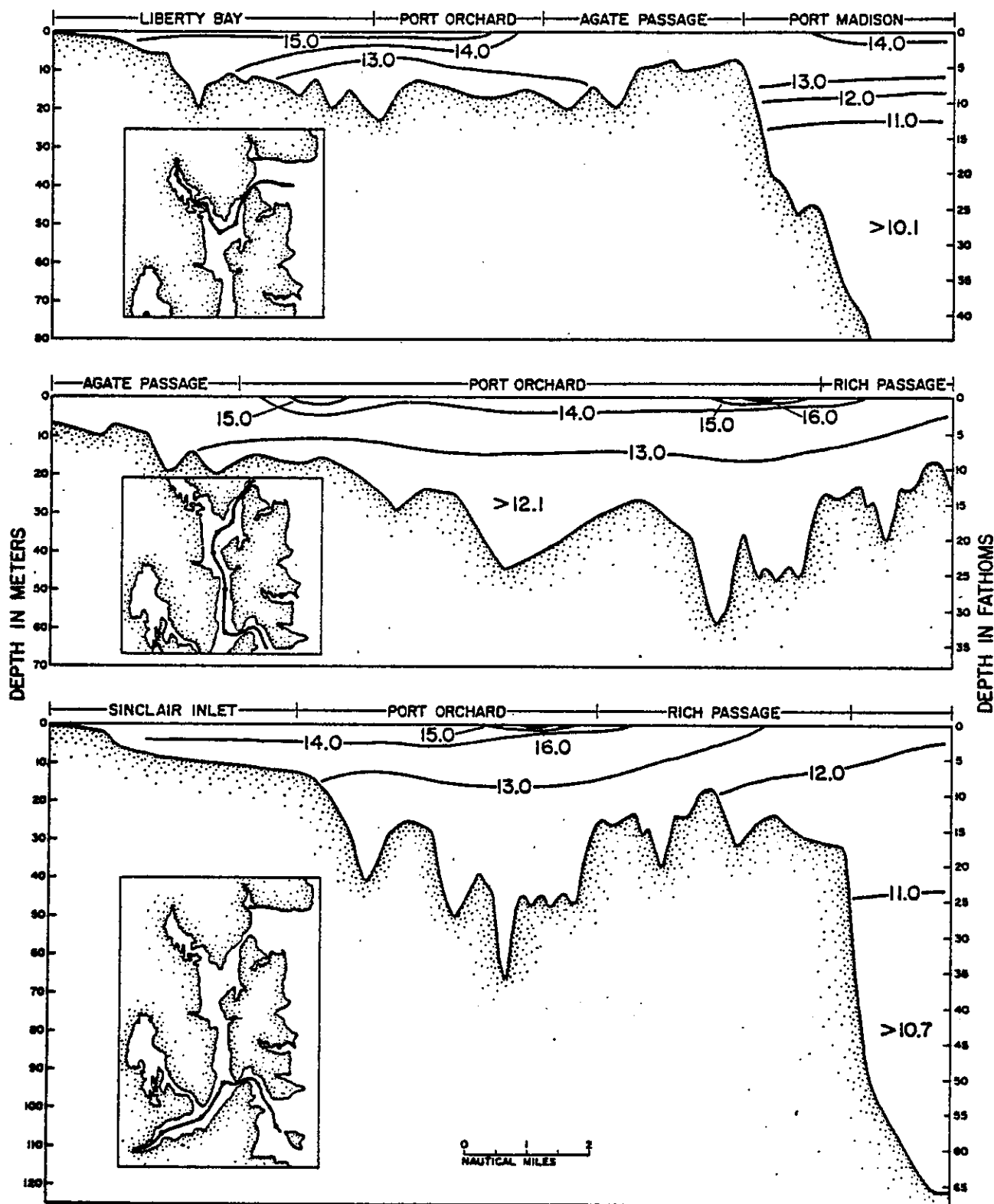
Figure III-19. Vertical Distribution of Temperature (°C) in the Port Orchard System, July 15, 1975.

Source: Lincoln and Collias, 1975.
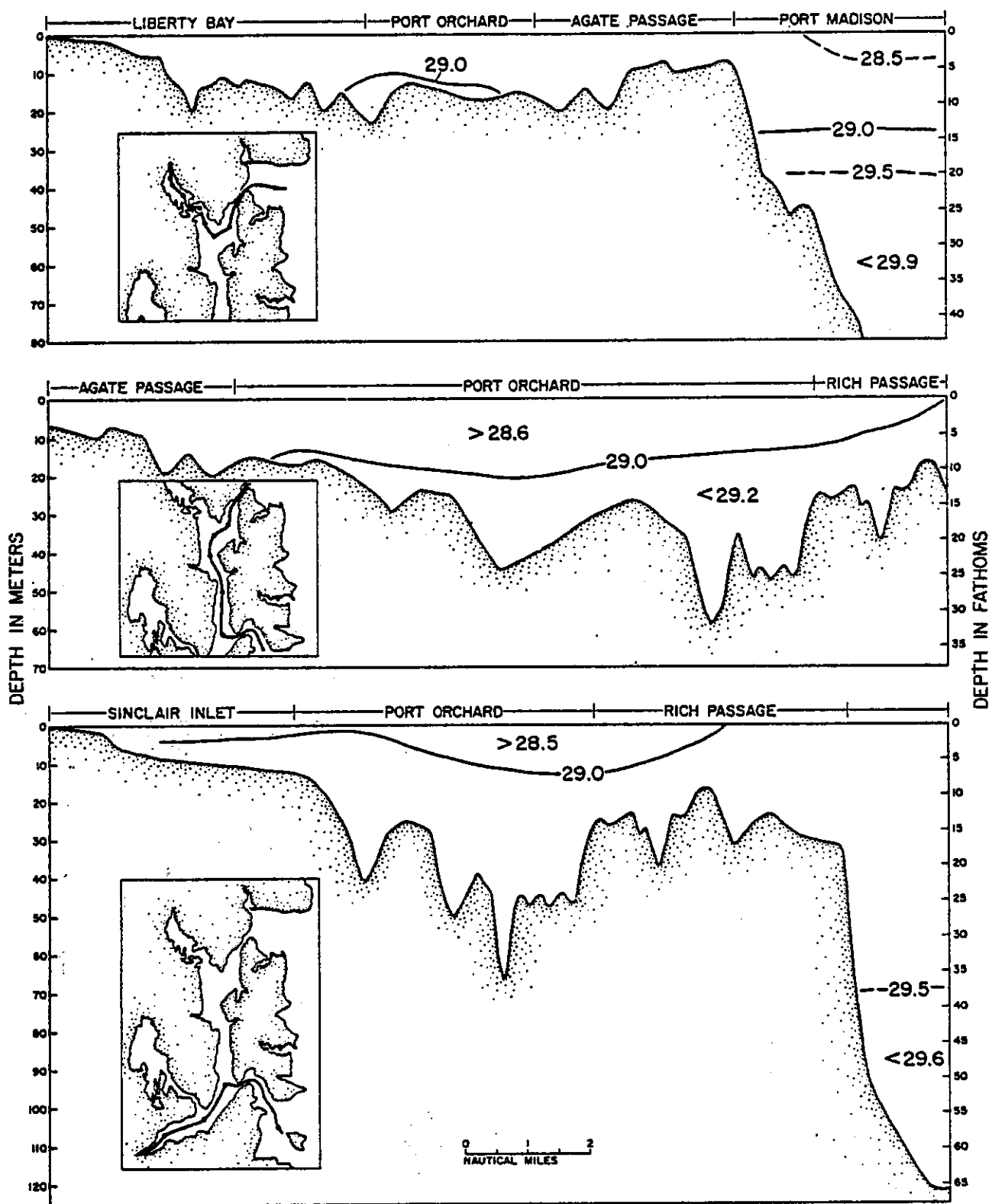
Figure III-20. Vertical Distribution of Salinity (°/oo) in the Port Orchard System, July 15, 1975.

Source: Lincoln and Collias, 1975.
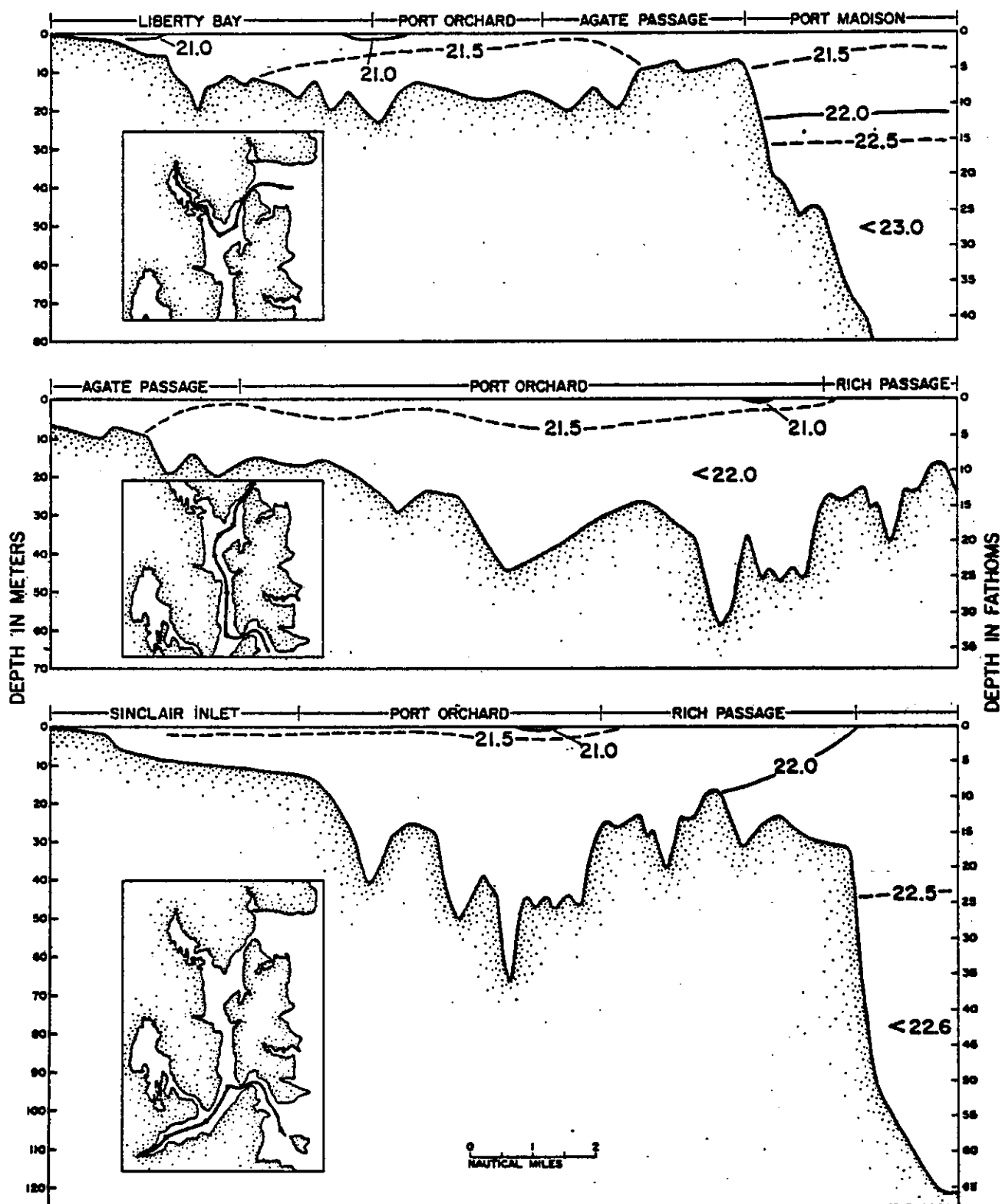
Figure III-21. Vertical Distribution of Density (sigma-t) in the Port
Orchard System, July 15, 1975.

Source: Lincoln and Collias, 1975.
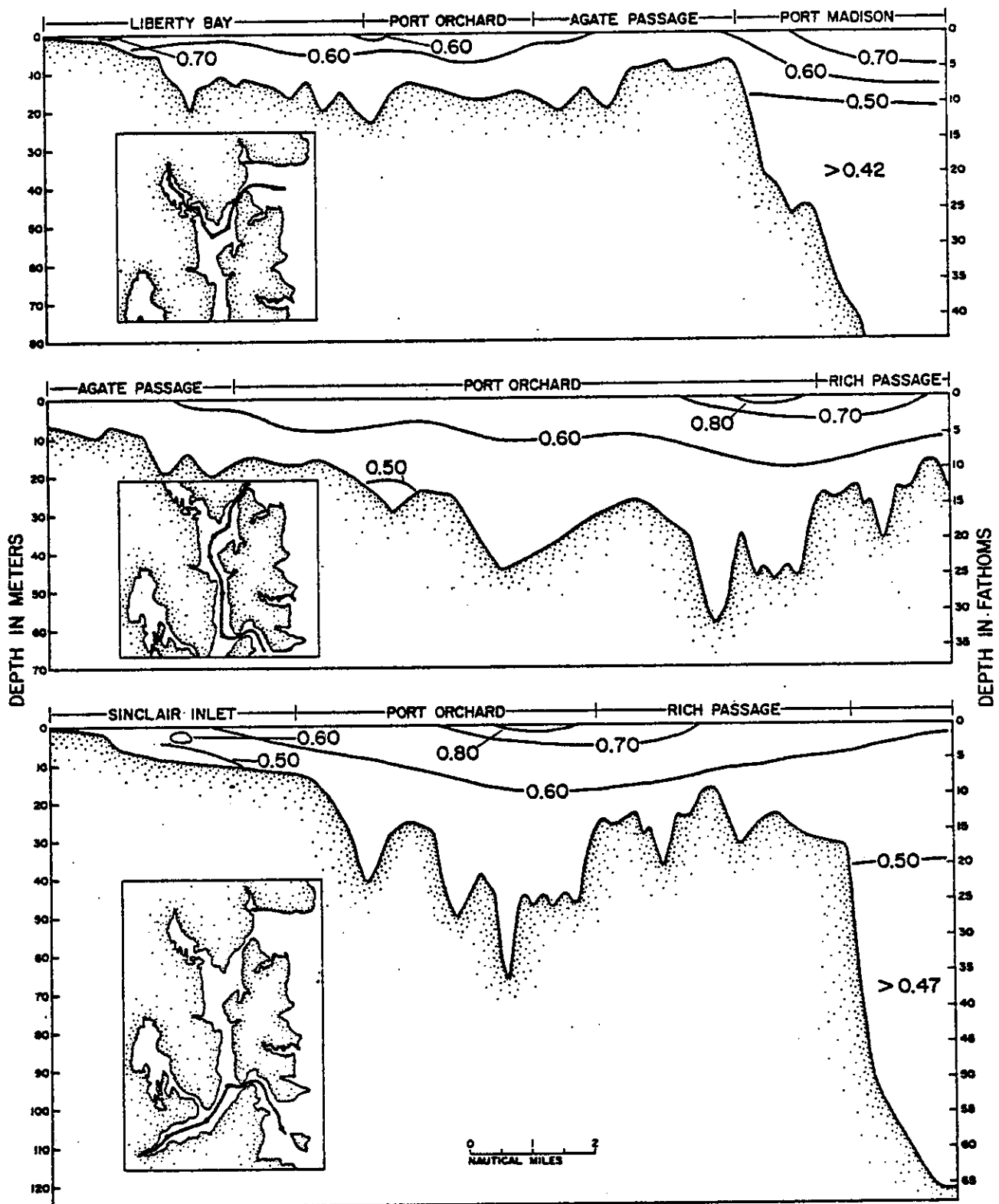
Figure III-22. Vertical Distribution of Dissolved Oxygen (mg-at/l) in the Port Orchard System, July 15, 1975.

Source: Lincoln and Collias, 1975.

-50-
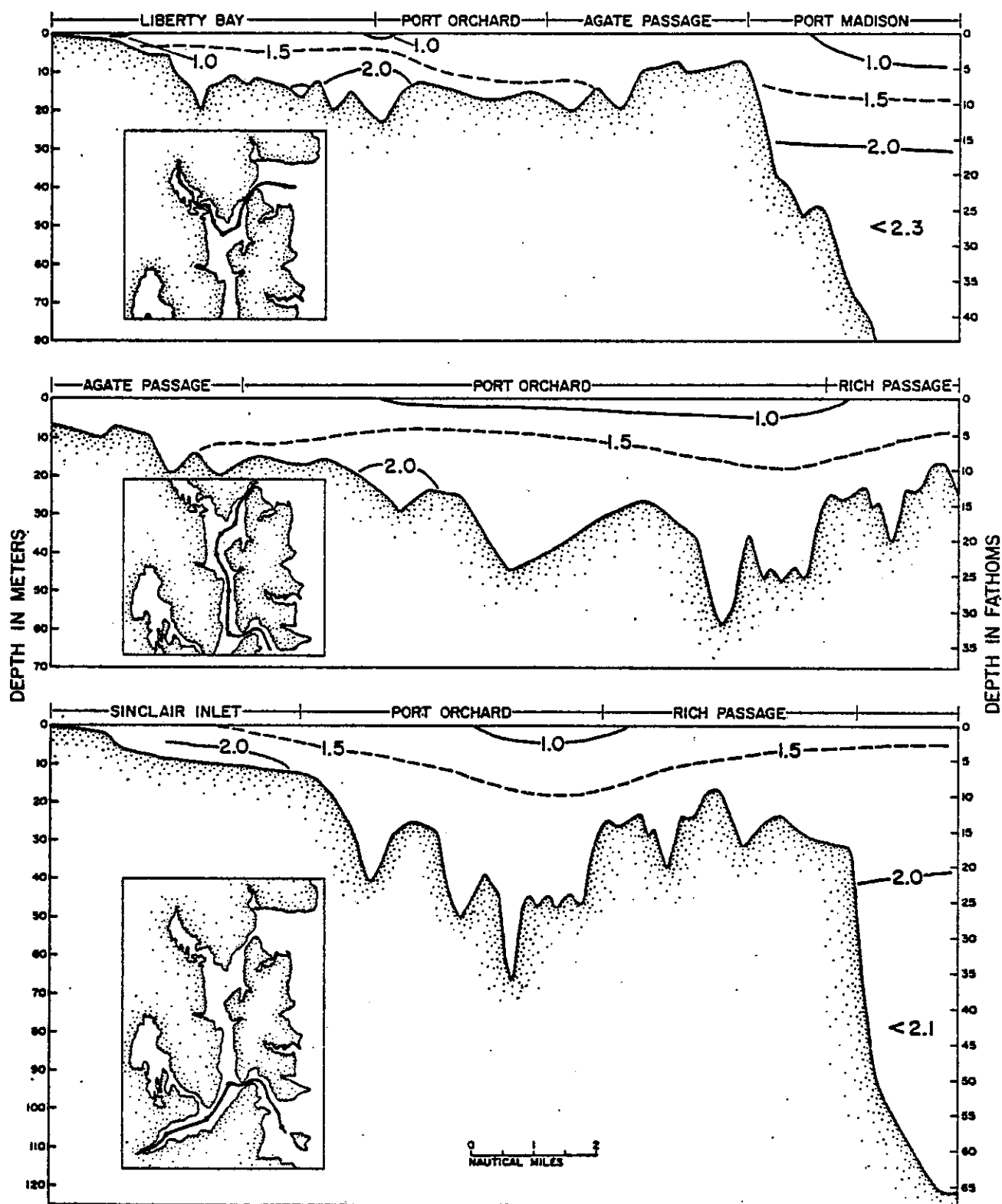
Figure III-23. Vertical Distribution of Phosphate (μg-at/l) in the Port Orchard System, July 15, 1975.

Source: Lincoln and Collias, 1975.

-51-
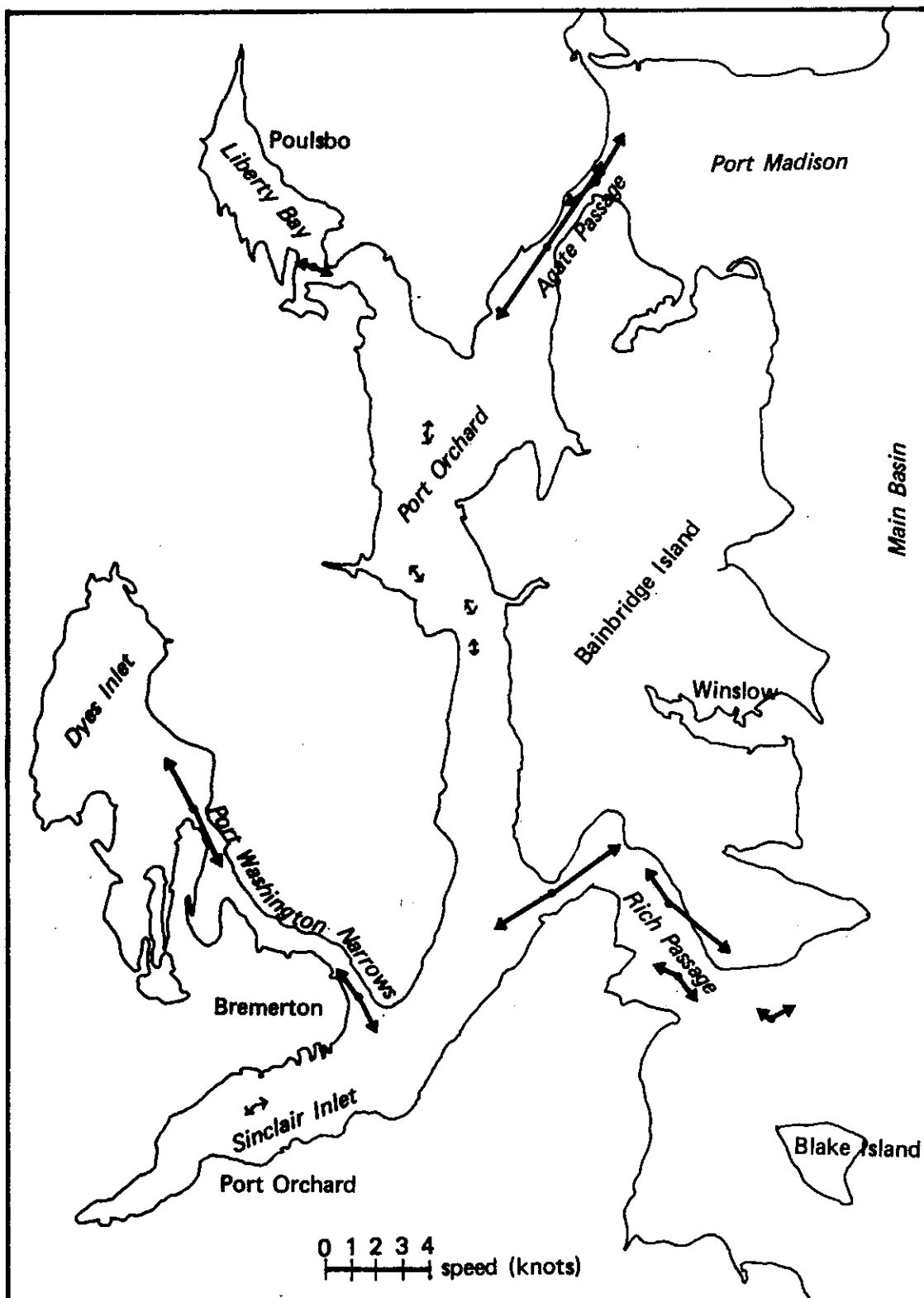
Figure III-24. Tidal Currents in the Port Orchard System. Values in Sinclair Inlet and Port Orchard are from the Tidal Model, all others are from NOS, 1980b.

TABLE III-1

TIDAL CURRENTS IN THE PORT ORCHARD SYSTEM

| | Average Maximum Currents | | | |
| | Flood | | Ebb | |
Location	Direction (°T)	Speed (m/sec)	Direction (°T)	Speed (m/sec)
Agate Passage				
North End	230	0.6	030	0.9
South End	215	1.7	035	1.9
Liberty Bay				
Entrance	280	0.4	115	0.4
Rich Passage				
Approach	300	0.1	070	0.5
East End	320	0.4	145	0.6
Pleasant Beach	330	0.7	130	1.4
West End	240	1.2	055	1.6
Port Washington Narrows				
North End	330	1.1	155	1.1
South End	325	0.5	155	0.9

Source: Tidal Current Tables (NOS, 1980b)

Tidal currents measured in the hydraulic tidal model (Lincoln and Collias, 1975) were weak and mainly bidirectional along the axis of Sinclair Inlet, with ebb currents slightly stronger than flood currents. The maximum measured ebb current was 0.3 knots during a spring tide. Currents near University Point in Port Orchard were found to be southerly at the start of a flood tide, reversing to northerly through the start of ebb flow. Maximum tidal currents measured in the model were 0.25 knots. Currents in northern Port Orchard were southerly during flood and northerly during ebb. No net circulation has been observed around Bainbridge Island either in the model or in the field.

It should be remembered that winds are not included in the hydraulic tidal model. Because much of this area is shallow and also because the tidal currents are generally weak, strong winds in this area should have a significant effect on the circulation.

The dense water found off Manchester which enters the system through Rich Passage is discharged from Colvos Passage. The Colvos Passage water, comprised of surface and deep East Passage water and some Southern Sound water, discharges around both sides of Blake Island. This water is denser, higher in nutrients, and lower in dissolved oxygen than typical upper layer water of the Main Basin. According to current patterns observed in the hydraulic tidal model and presented in the Tidal Current Tables some of the Colvos Passage discharge can enter Rich Passage and could advance to Sinclair Inlet or Port Orchard.

FLUSHING

Dispersion studies conducted in the hydraulic tidal model have indicated that flushing in most of the Port Orchard system is slow (Lincoln and Collias, 1975). In Sinclair Inlet, there is a small outward tidal transport during spring tides. However, in general, the weak oscillating tidal currents present in the inlet generate poor flushing.

Wind effects which cannot be incorporated into the hydraulic tidal model may have a significant effect on flushing in this area. Southwesterly winds would aid flushing in Sinclair Inlet by pushing out surface water and forcing a return flow at depth. Southerly and/or northerly winds will aid flushing in Port Orchard. No data are available for estimating the flushing times possible under different wind conditions.

BUDD INLET AND THE SOUTHERN SOUND

The Southern Sound is a complex area consisting of many channels and inlets (Figure III-25). Very little data exist for Budd Inlet so the discussion in this section focuses primarily on other Southern Sound inlets. The little information available for Budd Inlet suggests it is similar to other Southern Sound inlets (Olcay, 1959).

DISTRIBUTION OF WATER PROPERTIES

Water property distributions in the Southern Sound have been presented by Collias et al. (1974), and Olcay (1959). In most of the inlets there is an inverse relationship between rainfall and the vertically averaged salinity. In general the average salinity and density decrease from The Narrows to the head of the system at Oakland Bay. Also, the annual range of temperature, salinity and density increase toward Oakland Bay.

Trends in salinity and temperature in individual inlets have been observed. Typically, salinity decreases from the mouth to the head of the inlet. Also, the temperature is generally lower in the winter and higher in the summer at the heads of the inlets.

The lowest dissolved oxygen concentrations and highest soluble phosphate concentrations occur in October (Olcay, 1959). This is coincident with the time of maximum salinity in the Main Basin. Highest dissolved oxygen and lowest phosphate values occur in May or June.

Water property distributions observed in Carr Inlet are shown in Figure III-26. These distributions illustrate trends in water property values which are typical of Southern Sound inlets.

CIRCULATION

No major circulation studies have been conducted in the Southern Sound. Very general circulation patterns can be derived from Tide Prints (McGary and Lincoln, 1977) and from the Tidal Current Tables (NOS, 1980b). Average maximum flood and ebb currents for several locations in the Southern Sound are listed in Table III-2.
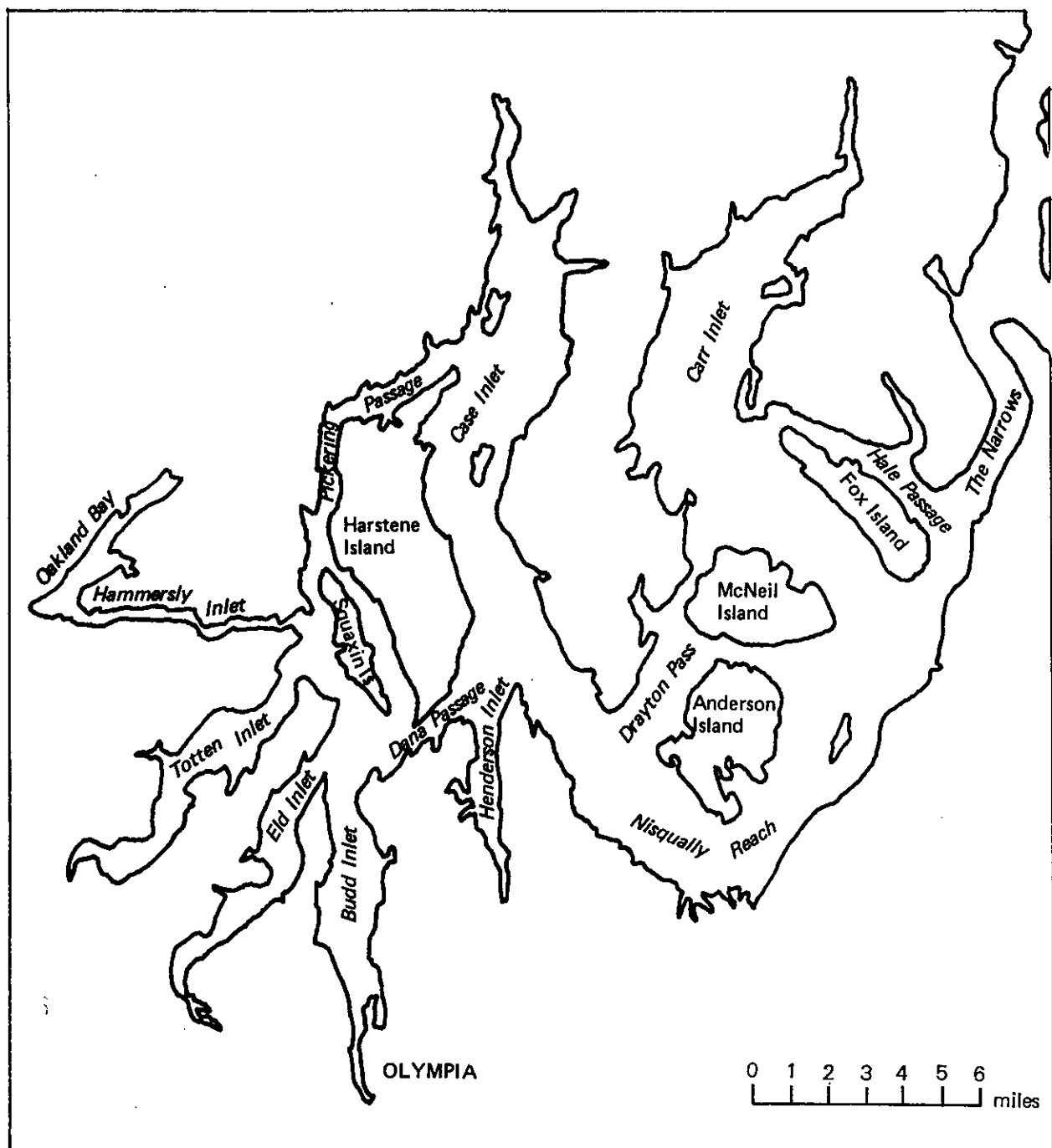
Figure III-25. Area Map of the Southern Sound.

PROFILE LOCATION CHART
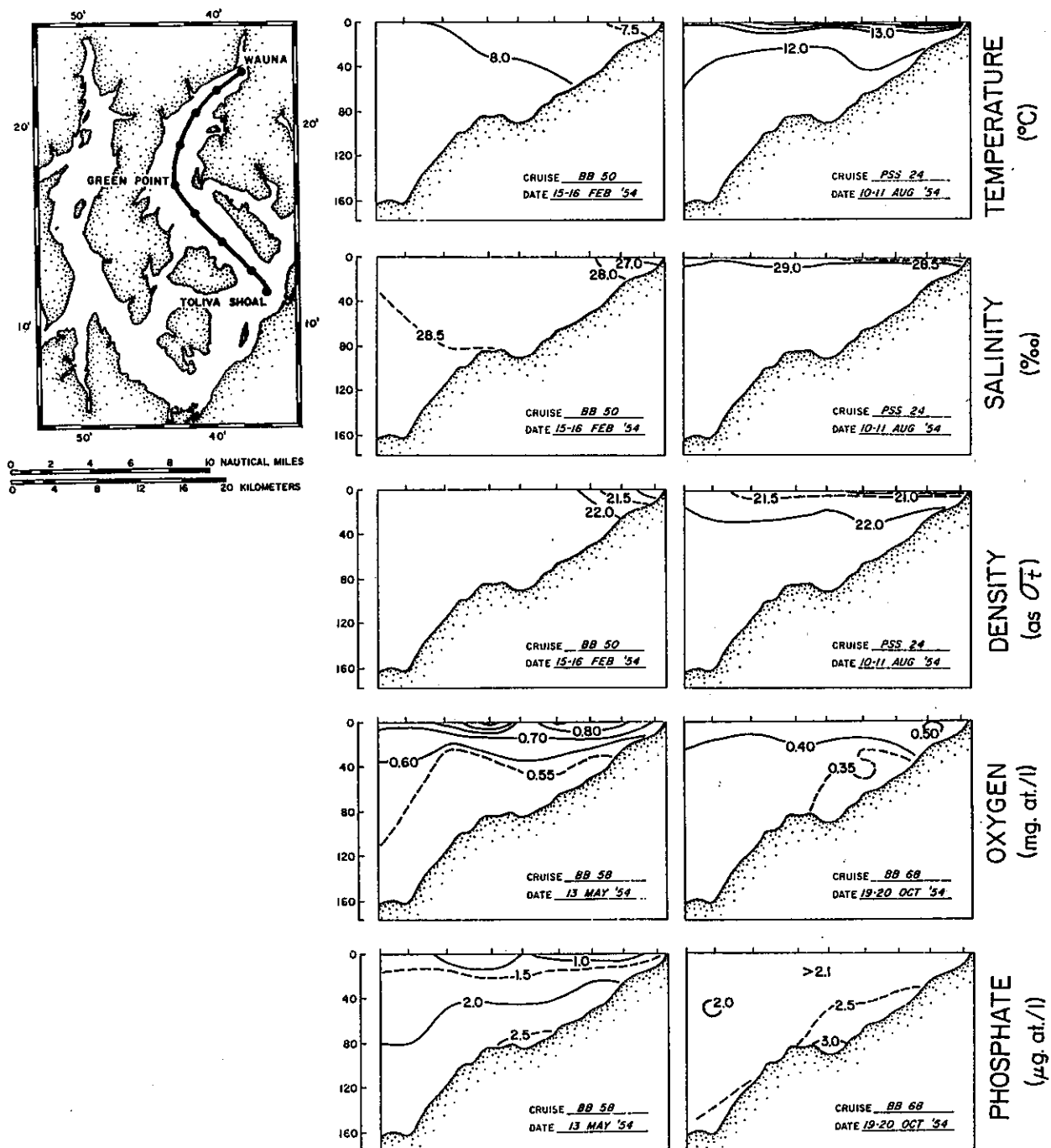
Figure III-26. Water Property Distributions in Carr Inlet.

Source: Collias et al., 1974.

TABLE III-2

TIDAL CURRENTS IN THE SOUTHERN SOUND

Location	Average Maximum Currents			
	Flood		Ebb	
	Dir (|T)	Speed (m/sec)	Dir (|T)	Speed (m/sec)
Hale Passage, west end	300	0.7	120	0.9
Nisqually Reach	260	0.6	045	0.6
Dana Passage	250	0.8	075	1.1
Budd Inlet, entrance	235	0.4	030	0.2
Eld Inlet, entrance	225	0.5	030	0.3
Totten Inlet, entrance	245	0.9	055	0.5
Hammersley Inlet	285	1.2	100	1.2
Pickering Passage, south end	190	0.7	015	0.7
north end	250	0.3	065	0.3

Source: Tidal Current Tables (NOS, 1980b)

FLUSHING

Olcay (1959) calculated flushing by looking at the change in
salinity which occurred over an extended dry period subsequent to
a large input of freshwater from heavy local rains. He calculated
a "half-life" flushing period of eight days for Oakland Bay. This is
equivalent to 90 percent replacement occurring in five weeks.

He could not calculate flushing in Budd Inlet since the salinity returned to normal conditions sometime before the first sampling period after the heavy rains. Olcay concluded that Budd Inlet had a much faster flushing rate than Oakland Bay. He said this could be attributed to:

1. the lack of a sill at the entrance to Budd Inlet

2. the wide mouth of the inlet which opens to a well mixed tidal channel or

3. the lack of turbulent mixing allowing surface water to escape from the inlet

The third explanation implies that surface water flushing may be rapid while deep water flushing could be considerably slower.

Southerly winds which occur primarily in winter will aid flushing in Budd Inlet and other inlets which open to the north. The same winds will retard flushing in Case and Carr Inlets. Northerly winds will have the opposite effect, enhancing flushing in Carr and Case Inlets and retarding flushing in Budd Inlet.

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CHAPTER 4. SEDIMENTATION

SEDIMENT SOURCES

The principal sources of sediment entering an estuary are typically rivers, shore erosion, biological production and advective inputs. In Puget Sound, biological production is not considered to be a significant sediment source. Advective transport of sediments result in essentially no net input. Fluvial inputs and sediments derived from shoreline erosion are the major sediment sources to Puget Sound.

Biological Production

The annual average rate of biological production in Puget Sound is approximately 400 gC/m^2 yr. This yields an average total input of 1.6 x 10^3 metric tons of sediment per year (mt/yr) assuming 2 g dry weight/gC and an area of 1985 km^2. Production rates are discussed in the Phytoplankton section of Chapter 5.

Advective Inputs

Since the distribution of suspended sediments in Admiralty Inlet is not well defined, the net transport of sediments through Admiralty Inlet can not be accurately calculated. However, estimates can be made based on measurements made just north of Admiralty Inlet by Baker et al. (1978). They found that, away from the influences of major rivers, sediment concentrations were approximately uniform from surface to bottom. Assuming the sediment concentrations in Admiralty Inlet are also uniform, then the inflow and outflow of sediments through Admiralty Inlet should be approximately equal.

Fluvial Inputs

The amount of sediment carried by a river depends on the carrying capacity of the river and on the sediment yield of the drainage basin. Long-term sediment discharge data collected by the USGS is available only for the Skagit and Duwamish Rivers. In order to estimate the sediment input from the other major rivers, it was assumed that rivers of a similar size and discharge pattern had similar sediment to water discharge ratios. Therefore, it was assumed that the Snohomish River is similar to the Skagit and that the Puyallup, Stillaguamish, and Nisqually are similar to the Duwamish.

Suspended sediment concentrations are routinely monitored in the Skagit River by the USGS, usually at intervals of one measurement of the suspended sediment concentration per month. To estimate the

annual suspended sediment discharge from the Skagit, these monthly values were assumed to represent suspended sediment concentrations for the entire month. These concentrations and daily water discharge rates were used to calculate monthly suspended sediment discharge rates. Monthly values were averaged over four years to provide an estimate of the average annual suspended sediment discharge. This was calculated to be 1.1×10^6 mt/yr. The ratio of sediment discharge to water discharge was estimated to be 7.1×10^{-5} mt/m^3.

In the mid 1960's, the USGS conducted intensive studies of the Duwamish River estuary (Santos and Stoner, 1972). This included daily measurements of suspended sediment concentrations over a three year period. The average annual sediment discharge for the period was 1.7×10^5 mt/yr. During these same three years, the average annual water discharge was 2124 m^3/min yielding a sediment to water discharge ratio of 1.5×10^{-4} mt/m^3.

In addition to suspended sediment inputs, rivers also carry sediments as bedload. Typically bedload is assumed to be equal to 10 percent of the suspended load. The few measurements made in the Snohomish River indicate bedload to be 5 to 6 percent of the suspended load (USGS, 1976). In the Duwamish River bedload was observed to be 20 to 40 percent of the suspended load with the percentage decreasing as discharge increased (Santos and Stoner, 1972). Bedload for all major rivers in Puget Sound was therefore assumed to be 20 percent of the suspended load. This figure is most likely an overestimate.

Estimates, based upon the assumptions identified above, of sediment discharge rates for all six major rivers entering Puget Sound are presented in Table IV-1. These estimates were found to agree within 10 percent of recent estimates of sediment discharge calculated using rating curves (Jeff Borgeld, University of Washington, Dept. of Oceanography, personal communication).

Shoreline Erosion

Shoreline erosion has been estimated to contribute 75 percent of the total sediment input to Puget Sound (Wang, 1955). Wang calculated that since the last glaciation (15,000 years ago) a total of 1.9×10^{10} m^3 of sediment have eroded from the shorelines of Puget Sound. This figure yields an annual rate of 1.3×10^6 m^3/yr. Assuming a density of 2.0 g/cm^3 the annual sediment supply from shoreline erosion would be 2.6×10^6 mt/yr.

Very little other work has been done to determine the rate of shoreline erosion. There are two documented mechanisms causing bluffs to erode. One, discussed previously, is due to the unstable arrangement of sands overlying clays. Groundwater not absorbed by the clay deposit mobilizes the sands, causing slumping. Bluffs are also eroded by direct

TABLE IV-1

WATER AND SEDIMENT DISCHARGE RATES FOR
MAJOR RIVERS ENTERING PUGET SOUND

River	Annual[a] Suspended Sediment Discharge (mt/yr)	Annual[b] Water Discharge (m^3/min)	Sediment to Water Ratio (mt/m^3)	Annual[c] Suspended Sediment Discharge (mt/yr)
Skagit	1.1×10^6	28,594	7.1×10^{-5}	
Snohomish		17,194	7.1×10^{-5}	6.4×10^5
Duwamish	1.7×10^5	2,117	1.5×10^{-4}	
Puyallup		5,753	1.5×10^{-4}	4.6×10^5
Stillaguamish		5,065	1.5×10^{-4}	4.0×10^5
Nisqually		2,182	1.5×10^{-4}	1.7×10^5

Total Suspend Sediment Discharge = 2.9×10^6 mt/yr

Total Sediment Discharge[d] = 3.5×10^6 mt/yr

a: Values based on measurements. Skagit data is from the USGS sources. Duwamish data is from Santos and Stoner source.

b: Based on USGS sources.

c: Values based on assumed sediment to water discharge ratio and water discharge measurements

d: Total sediment discharge equals 1.2 x suspended sediment discharge to include bedload

Sources: USGS, 1975, 1976, 1977, 1978, 1979
        Santos and Stoner, 1972

wave action. Waves constantly impinge on the base of the bluff thereby undercutting it, causing sections of the bluffs to fall down. Either one of these mechanisms can predominate in an area or they may work together.

For example, the bluffs at Discovery Park, Seattle, are eroding primarily because of groundwater mobilization of sands (Tubbs et al., 1974). A study conducted using aerial photographs to measure bluff retreat at the park showed that the average rate of retreat along the entire length of the park was 0.3 m/yr. Thus, on the average, 13.5 m^3 of sediment have been eroded per meter length of shoreline each year, assuming an average bluff height of 45 m.

The USGS is presently conducting studies measuring shoreline erosion in the Strait of Juan de Fuca and surrounding areas (R. Keuler, USGS, personal communication). The results at this time are only preliminary and will probably change somewhat as their work progresses. However, some numbers are available to make preliminary calculations.

There are three factors to consider while making erosion estimates: 1) the energy of the area has a direct relationship to the amount of material eroded, 2) not all of the shoreline is erodable, 3) some of the material eroded will remain on the beach or in the nearshore system. For high energy regions the estimated erosion rate is 7-15 m^3/m-yr. This would be valid for areas such as the Strait of Juan de Fuca where the shoreline is exposed to fairly constant heavy wave attack. In moderate energy regions 2-5 m^3/m-yr is considered reasonable and in low energy regions 1 m^3/m-yr would be expected (R. Keuler, USGS, personal communication). Moderate energy regions such as the Main Basin and Admiralty Inlet are more protected from the wind than high energy regions but still experience strong wave energy at times. Low energy regions such as the Southern Sound rarely experience high energy waves. These rates are not dependent on bluff heights. It appears that taller bluffs erode more slowly than shorter bluffs. However, the volume of material eroded per year seems to be approximately constant for similar energy regions.

Based on these erosion rates and also assuming that 20 percent of the eroded material stays in the beach system (R. Keuler, personal communication), and that 50 percent of the shoreline is erodable, erosion rates for Puget Sound have been calculated. The latter assumption is not based on measured data but rather is a "best guess." If the actual amount of erodable shoreline was anywhere between 25 to 100 percent, the value chosen would be in error by at most a factor of two. This possible error is comparable with the uncertainty range of other input values. Erosion estimates are presented in Table IV-2.

The virtual absence of river sediments on beaches in the Puget Sound area and the abundance of sand in bottom sediments is indicative

TABLE IV-2

ESTIMATED SHORELINE EROSION RATES IN PUGET SOUND*

Area	Total Shoreline (m)	Erodable Shoreline		Erosion Rate $m^3/m\text{-}yr$	Amount Eroded m^3/yr	Input To Puget Sound	
		%	m			m^3/yr	mt/yr
Admiralty Inlet	1.78×10^5	50	8.90×10^4	5	4.5×10^5	3.6×10^5	7.1×10^5
Main Basin	5.34×10^5	50	2.67×10^5	2	5.3×10^5	4.3×10^5	8.5×10^5
Southern Sound	6.21×10^5	50	3.11×10^5	1	3.1×10^5	2.5×10^5	5.0×10^5
Whidbey Basin	4.69×10^5	50	2.35×10^5	1	2.4×10^5	1.9×10^5	3.8×10^5
TOTAL	1.80×10^6	50	9.02×10^5	-	1.5×10^6	1.2×10^6	2.4×10^6

* Based upon assumptions outlined in the text.

of the major contribution made by bluff eroded material to the
system. This source could contribute much more than the calculated
amount.

Total Inputs

Sediment input calculations are summarized in Table IV-3. The
estimate of sediment input from shoreline erosion calculated here agrees
well with Wang's (1955) calculations. However, the estimate of fluvial
inputs is about 4 times the value that Wang used. So instead of esti-
mating 75 percent input from shoreline erosion and 25 percent input from
river, we calculate 40 percent input from shoreline erosion and 60 percent
input from rivers. It is important to remember that many assumptions,
previously explained, had to be made to obtain these estimates. There-
fore, they should be regarded as order of magnitude estimates only.

Sediment inputs are not spatially or temporally uniform. Table IV-3
shows the percent of total input entering each of four major subdivisions
of Puget Sound. It is reasonable to assume that shoreline erosion would
occur more in the winter than summer due to storms and rain which
predominate in the winter. The majority of river sediments also enter
the system in the winter as shown in Table IV-4.

SEDIMENT DISTRIBUTIONS

Surface sediment textural data for the Puget Sound region was
compiled by Roberts (1974). These data were also used to produce maps
of surface sediment type distributions for the region. The maps are not
reproduced here but simplified descriptions and maps are presented
below.

Before discussing the sediment distributions, it is important
to realize that the variability between samples only a few feet apart
can be quite large. Bader (1953) conducted a study on the local varia-
bility of surface sediments in Puget Sound. Triplicate cores spaced one
foot apart were collected at 60 locations in the Main Basin between
President' Point and Richmond Beach. Bader found that local variability
increased upslope with the largest variability occurring at 60 to 90 m.
The greatest differences occurred in the smaller diameter sand sizes.
Dexter et al. (1979) found differences of up to 36 percent in sand
content between samples collected within 20 m of each other in Elliott
Bay. They also found similar differences in sediment texture with depth
in cores, implying significant temporal variations in sedimentation.

The large spatial and temporal variability observed in some
surface sediments has been poorly investigated in most areas and

TABLE IV-3

ESTIMATED TOTAL SEDIMENT INPUT BY AREA

Area	Fluvial[a] Input		Shoreline[b] Input		Total Input	
	mt/yr	%	mt/yr	%	mt/yr	%
Admiralty Inlet	-	0	7.1×10^5	29	7.1×10^5	12
Main Basin	7.5×10^5	21	8.5×10^5	35	1.6×10^6	27
Southern Sound	2.0×10^5	6	5.0×10^5	20	7.0×10^5	12
Whidbey Basin	2.5×10^6	73	3.8×10^5	16	2.9×10^6	49
TOTAL	3.5×10^6	100	2.4×10^6	100	5.9×10^6	100

a: Data are from Table IV-1 and include both suspended load and bedload (total input equals 1.2 x suspended load to account for bedload).

b: Data are from Table IV-2.

TABLE IV-4

TEMPORAL VARIATION OF FLUVIAL INPUTS

	Skagit %R*	Skagit %T+	Snohomish %R	Snohomish %T	Puyallup %R	Puyallup %T	Stillaguamish %R	Stillaguamish %T	Duwamish %R	Duwamish %T	Nisqually %R	Nisqually %T	Total %
OCT	1	0.4	4	0.8	4	0.6	6	0.9	3	0.2	7	0.4	3
NOV	7	3	11	2	8	1	13	2	10	0.6	9	0.5	9
DEC	21	8	17	4	16	2	17	2	21	1.3	19	1.2	19
JAN	35	13	11	2	12	2	12	<2	15	0.9	14	0.9	21
FEB	4	<2	7	2	8	1	8	1	10	0.6	9	0.5	7
MAR	2	0.8	7	2	7	1	8	1	9	0.5	10	0.6	6
APR	2	0.8	7	2	6	1	8	1	9	0.5	7	0.4	5
MAY	6	2	11	2	9	1	10	1	9	0.5	5	0.3	7
JUN	8	3	11	2	11	2	7	1	6	0.4	6	0.4	9
JUL	6	2	6	1	8	1	4	0.6	3	0.2	4	0.2	5
AUG	4	<2	4	0.8	6	1	3	0.4	2	0.1	4	0.2	4
SEP	4	<2	4	0.8	5	1	4	0.6	3	0.2	6	0.4	5
TOTAL	38		22		15		13		6		6		100

* % R is the percentage of each river input occurring during that month.
+ % T is the percentage of the total input contributed by each river during that month.

Sources: USGS, 1976, 1977, 1978, 1979; Santos and Stoner, 1972.

is not represented on the maps. Often only one sample has been taken in an area and must be assumed to be representative of the entire area. Variability between samples must be kept in mind when reviewing the sediment distributions.

Surface sediment distributions for Admiralty Inlet and the Main Basin including Elliott and Commencement Bays are presented in Figure IV-1. Distribution maps for the Port Orchard system and the Southern Sound are shown in Figures IV-2 and IV-3, respectively. The sediment types used in the maps are defined in Table IV-5.

Several general features are apparent in the figures. In open regions, such as the Main Basin, bays and most inlets, there is usually mud in the deepest areas. The grain size usually increases with decreasing depth. In the sill areas gravel and sand predominate. In narrow channels such as Dana, Rich, and Agate Passages the bottom is primarily sand with some gravel and/or mud also present.

SEDIMENT TRANSPORT

Transport Processes

As sediments enter Puget Sound from rivers several processes determine the fate of the material. Suspended sediments are affected by the processes of turbulent mixing, flocculation and resuspension. General transport processes are explained in several books (e.g., Stanley and Swift, 1976) and are briefly summarized here.

Sedimentation is a function of particle settling rate, current speed and turbulence - faster currents and greater turbulence limit the deposition of fine material. When particles in fresh water encounter saltwater, they tend to become attracted to each other and form flocs. These act as larger particles and sink at a much faster rate than the individual particles making up the floc. Once deposited on the bottom, resuspension can occur when the boundary shear stress exceeds the critical stress of the bed. The former is related to the velocity profile but the latter is a complex function of the geometry of the sediment water interface and the texture of the sediments. In general, as the current velocities increase, the grain size of the sediments also increases; however, prediction based on average current speeds can be in error. Thus, bed sediment distributions are a reflection of sediment sources and transport conditions in the area.

Very little work has been done measuring sediment transport in Puget Sound. River plumes have been tracked to identify the extent of suspended sediment transport in the surface waters (Feely and Lamb, 1979; Baker et al., 1978), and two site-specific studies were made in
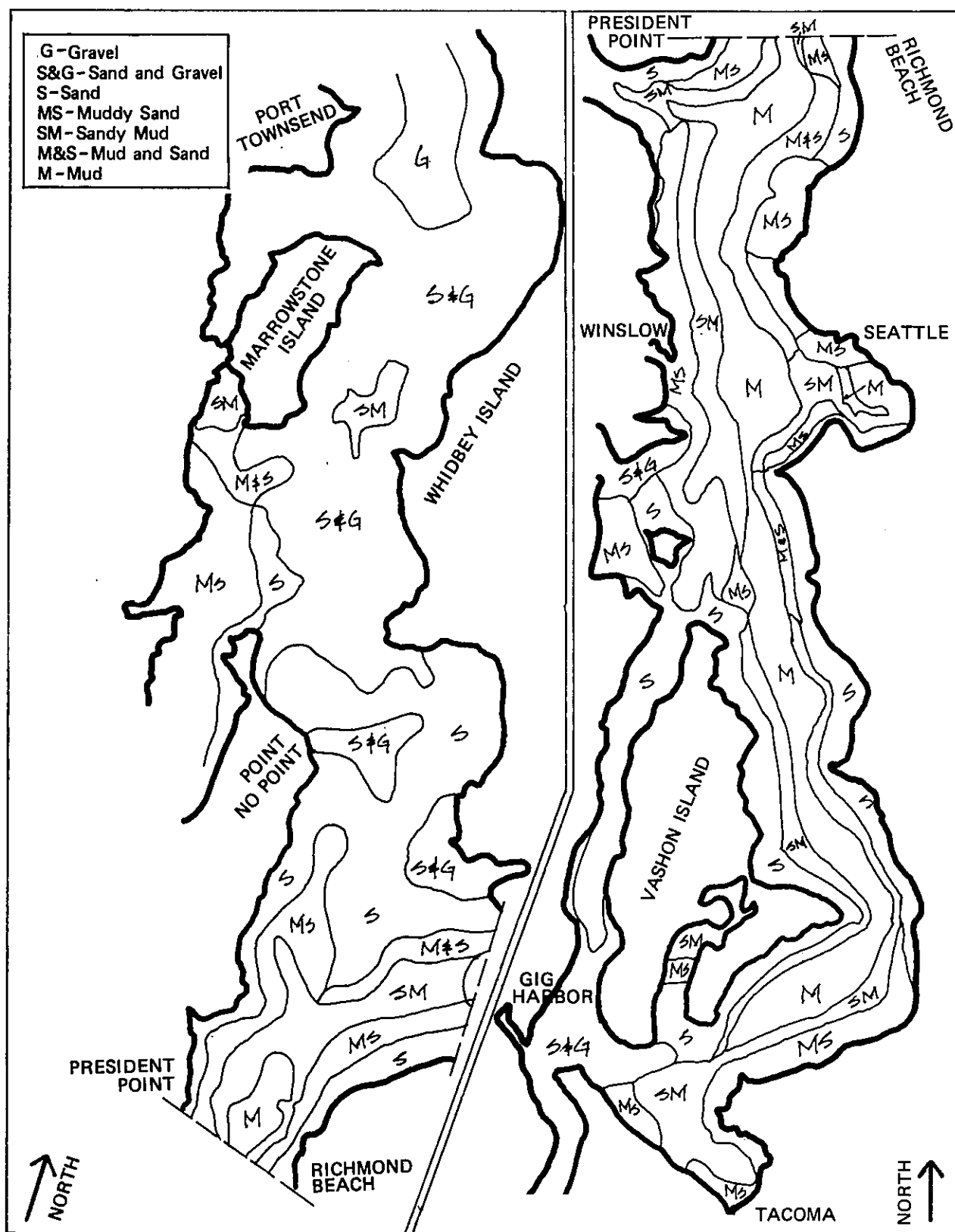
Figure IV-1. Simplified Sediment Distribution in the Main Basin and Admiralty
        Inlet. No data were available for unlabled areas.
Source: Roberts, 1979.
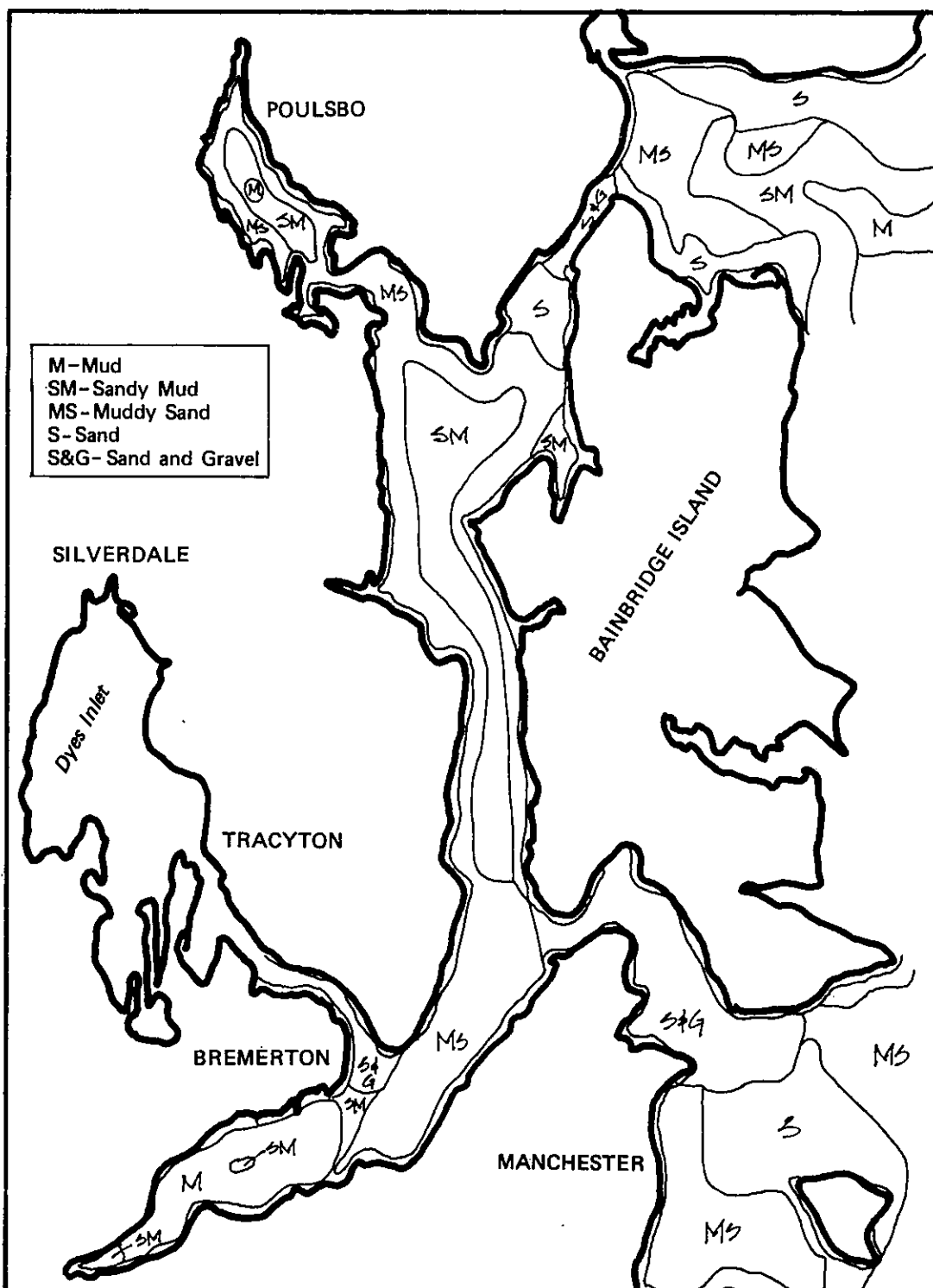
Figure IV-2. Simplified Sediment Distribution in the Port Orchard System. No data were available for unlabeled areas.

Source: Roberts, 1979.
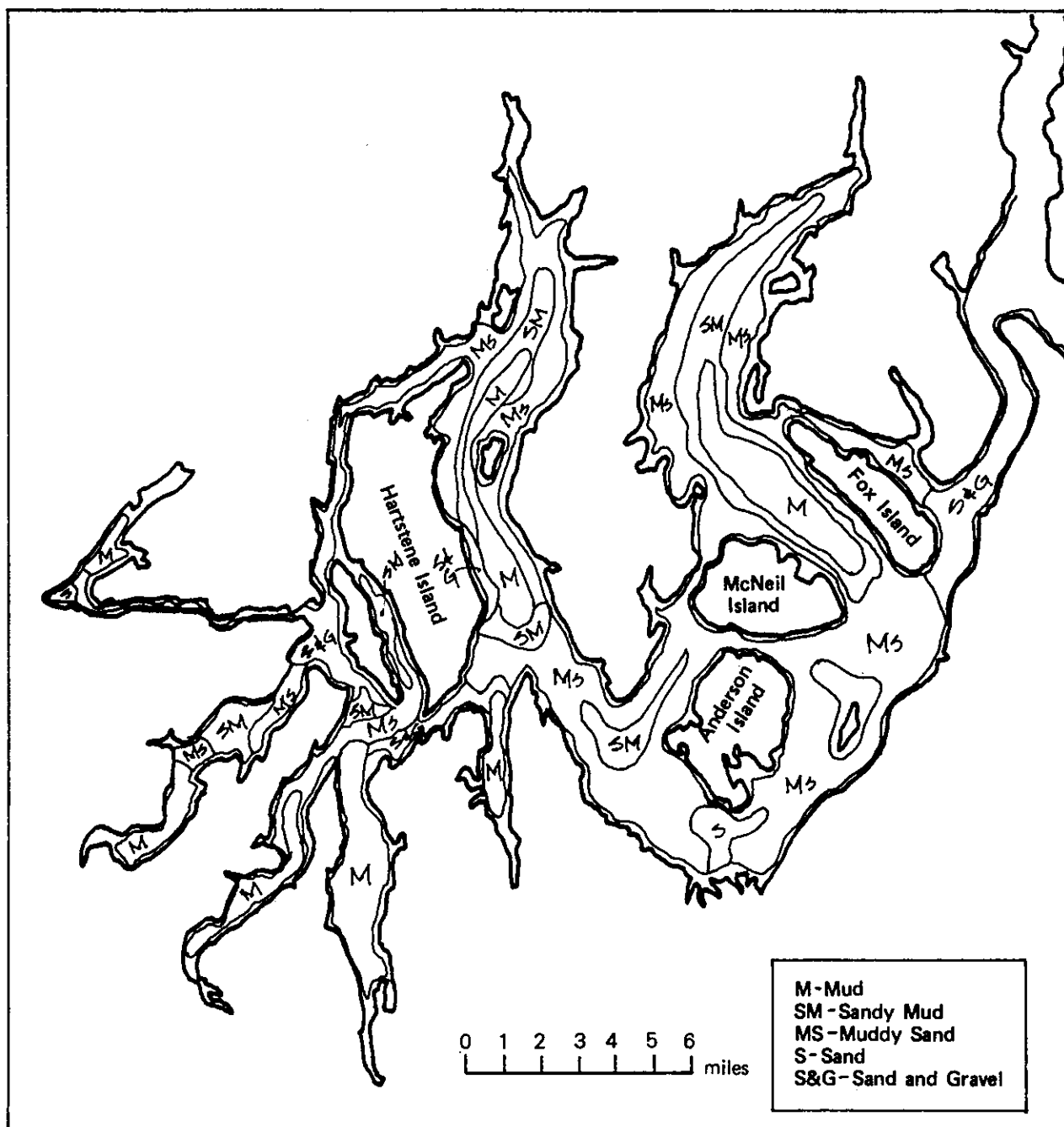
Figure IV-3. Simplified Sediment Distribution in the Southern Sound. No data were available for unlabeled areas.

Source: Roberts, 1979.

TABLE IV-5

DEFINITION OF SEDIMENT TYPES

Class Name[a]	Particle Diameter
Gravel	greater than (>) 2.00 mm
Sand	0.063 to 2.00 mm
Mud	less than (<) 0.063 mm

Sediment Type[b]	Composition		
	Gravel	Sand	Mud
Gravel	>80%	<20%	<20%
Sand	<10%	>80%	<10%
Mud	<10%	<10%	>80%
Muddy Sand	<10%	50-90%	10-40%
Sandy Mud	<10%	10-40%	50-90%
Gravel and Sand	unknown combination of gravel and sand		
Mud and Sand	unknown combination of mud and sand		

a   Class names are based on the size of individual particles

b   Sediment types use class names which describe the bulk of the sediment in the sample

relation to dredge disposal areas (Nittrauer and Sternberg, 1975; Dexter et al., 1979).

River Plume Studies

Whidbey Basin receives about one half of the total sediment input to Puget Sound (Table IV-3). A study on the dispersal of suspended sediment from the Skagit River using LANDSAT imagery (Feely and Lamb, 1979) showed that plumes from the Skagit are most pronounced during the summer. Sediments were traced as far south as the middle of Saratoga Passage and north to Deception Pass. During ebb tides the sediment plume could be seen exiting through Deception Pass. During low river discharge the plume was confined to nearshore regions of Skagit Bay.

In a related study (Baker et al., 1978) sediment concentrations were measured throughout the water column in the area north of Whidbey Basin (Strait of Georgia, San Juan Archipelago, and the Strait of Juan de Fuca). Suspended sediment concentrations typically ranged from 0.5 to 2 mg/l with the highest concentrations near the Fraser River (8 mg/l) and Deception Pass (3 mg/l). In areas not directly influenced by river runoff, seasonal variability was insignificant. In these areas suspended matter concentrations were slightly higher in the surface and near bottom waters compared to the intervening water column. The higher values were presumably due to phytoplankton growth and fresh water runoff at the surface and sediment resuspension at the bottom.

These two studies indicate that fluvial suspended sediments are largely confined to the area of the visible river plume. This implies that the settling rate for these sediments is rapid. After deposition the sediments may be resuspended and move in the direction of the bottom currents.

Resuspension Studies

A study conducted in Dana Passage (Nittrauer and Sternberg, 1975) showed the average current to be 25 cm/sec, insufficient to move sediments in the area. However, during spring tides, currents frequently exceeded 50 cm/sec, sufficient for resuspension to occur. This was not unexpected considering the configuration of the passage and the bottom sediment type. Since Dana Passage is relatively narrow, tidal currents will be strong. The sand and gravel bottom indicate that fine material is not being deposited.

Preliminary results of an ongoing study of a dredged material disposal area in Elliott Bay (Dexter et al., 1979) indicate that currents in the area are too weak to erode bottom sediments. Elliott Bay is a relatively deep area where strong currents would not be expected. The bottom of Elliott Bay is predominantly more than 50 percent mud, which would also indicate that this is a depositional environment.

These two studies are examples of how transport conditions, determined from the configuration and sediment distribution in an area, can be consistent with conditions determined from current measurements. Narrow channels with sand and gravel bottoms such as Admiralty Inlet, Rich and Agate Passages, The Narrows, etc., should be non-depositional areas. Quiet embayments and very deep areas where the bottom sediments are primarily mud should be depositional. Examples of these depositional areas would include Liberty, Elliott and Commencement Bays; Sinclair, Budd, Eld, Case, and Carr Inlets; and the deep central part of the Main Basin.

SEDIMENTATION RATES

Sedimentation rates derived from ^{210}Pb dating have been reported by Schell et al. (1977). These rates, which range from 0.8 mm/yr. to 20.0 mm/yr. are presented in Table IV-6. The average sedimentation rate for all measurements was 5.6 mm/yr. Excluding the values for Hood Canal, the Main Basin sedimentation rate was estimated to be 6.1 mm/yr. Except for two points in Elliott Bay, rates have not been measured in the major embayments of interest to this study.

SEDIMENT BUDGET

In order to conserve mass, sediment inputs to Puget Sound must equal losses from the system. Therefore, sediments derived from rivers and shoreline erosion should balance the sediments deposited in Puget Sound.

The horizontal area of Puget Sound, at mean lower low water, including Whidbey Basin and excluding Hood Canal, is 1985 km^2. To achieve an average sedimentation rate of 0.6 cm/yr would require a sediment input of 1.19×10^{13} cm^3/yr. This is equivalent to 1.7×10^7 mt/yr assuming an average conversion factor of 1.4 g dry solids per cm^3 of wet sediment (Schell et al., 1976).

The total sediment input to Puget Sound was previously calculated to be 5.9×10^6 mt/yr (Table IV-3). Of this amount, 20 percent of the material eroded from the shoreline may remain in the nearshore system, while a significant amount of the river sediments are apparently deposited in the river estuary and do not enter the offshore region. Also, approximately 60 percent of the sediment input enters into Whidbey Basin and the Southern Sound. Most of this material will not enter the Main Basin but will be deposited in their receiving basins. However, even if all of the estimated sediment inputs were evenly deposited throughout Puget Sound, an extra 1.1×10^7 mt/yr of sediment would be required to maintain a sedimentation rate of 0.6 cm/yr. This extra amount is almost twice the calculated total sediment input.

TABLE IV-6
SEDIMENTATION RATES IN PUGET SOUND

Station Location N. Lat.	W. Long.	Area	Depth(m)	Sedimentation Rate (mm/yr)
48° 0.5	122° 43.0	Admiralty Inlet	15	1.6
47° 54.8	122° 30.7	Main Basin	160	3.1
47° 44.8	122° 25.7	Main Basin	283	2.0
47° 43.2	122° 26.7	Main Basin	200	10.0
47° 40.5	122° 25.7	Main Basin	100	4.5
47° 39.9	122° 27.8	Main Basin	230	5.0
47° 39.7	122° 28.4	Main Basin	252	Very large
47° 39.7	122° 28.2	Main Basin	246	3.4
47° 38.8	122° 29.2	Main Basin	190	3.9
47° 37.7	122° 24.9	Elliott Bay	175	10.3
47° 36.8	122° 26.9	Elliott Bay	196	8.1
47° 34.1	122° 27.1	Main Basin	250	3.7
47° 33.8	122° 25.4	Main Basin	157	3.9
47° 33.6	122° 28.1	Main Basin	196	9.0
47° 33.6	122° 28.1	Main Basin	183	5.9
47° 32.5	122° 24.9	Main Basin	187	10.2
47° 29.1	122° 30.1	Colvos Passage	102	2.2
47° 25.9	122° 23.9	East Passage	130	20.0
47° 23.8	122° 26.6	East Passage	7	2.2
47° 18.4	122° 28.4	East Passage	160	6.7
47° 48.1	122° 45.1	Hood Canal	118	1.1
47° 40.5	122° 47.1	Hood Canal	122	0.8

Source: Schell et al., 1977

Obviously, there is a major discrepancy between the calculated input and the amount needed for the measured sedimentation rate. Since many assumptions were made to obtain each of these numbers there are many possible reasons for this discrepancy. Possible explanations include:

1. the sedimentation rate determined by ^{210}Pb is too large

2. estimates of river input and/or shoreline erosion are too small

3. the estimate of the advective transport of sediments into the Sound is too small.

4. sedimentation rates in the areas measured are not representative of other areas in Puget Sound.

At this time there are too many unknowns to clearly describe the sedimentation rates in Puget Sound. Most likely, the difference between the calculated inputs and amount required for deposition, is due to a combination of the explanations presented above.

SEDIMENTATION SUMMARY

Sediments derived from shoreline erosion and from rivers are considered the major sediment sources to Puget Sound. To estimate the rate of fluvial inputs, the following assumptions were made:

1. Rivers of a similar size and discharge pattern have similar sediment to water discharge ratios

2. Once per month measurements of suspended sediment concentrations are representative of the concentration for the entire month

3. Bedload is equal to 20 percent of the suspended load

4. No sediments are deposited in the river estuaries - all enter Puget Sound.

The first two assumptions probably give a reasonable estimate considering the data available. The latter two should overestimate the river inputs. Usually a significant, but undetermined, amount of sediments will be deposited in the estuary and on the river delta.

The input of sediment from shoreline erosion was estimated using these assumptions:

1. Admiralty Inlet, the Main Basin, the Southern Sound, and Whidbey Basin have erosion rates of 5, 2, 1, and 1 $m^3/m-yr$, respectively

2. 50 percent of the shorelines throughout the Sound are erodable

3. 20 percent of the eroded material stays in the beach and nearshore system

The erosion rates and percent erodability are probably reasonable or conservative.

The total sediment input was estimated to be 5.9×10^6 mt/yr. Approximately 40 percent was derived from shoreline erosion while 60 percent was from rivers. Sediment inputs are neither spatially nor temporally uniform.

Surface sediment distributions were presented in Figures IV-1 through IV-3. Variability which is not represented on the maps can be significant in some areas. The fate of material entering Puget Sound is dependent on circulation, turbulent mixing, flocculation, and resuspension. Sediment distributions are a reflection of sediment sources and transport conditions.

Sedimentation rates derived from ^{210}Pb dating range from 0.8 mm/yr to 20.0 mm/yr. The average sedimentation rate for the Main Basin was estimated to be 6.1 mm/yr. To achieve this rate a sediment input of 1.7×10^7 mt/yr would be required. Assuming all of the estimated 5.9×10^6 mt/yr entered Puget Sound and was evenly distributed an extra amount of almost twice the estimated input would be required to maintain the sedimentation rate.

Most likely, the difference between the estimated input and the amount required for deposition is greater than the amount estimated here. Two justifications for this are:

1. A significant amount of fluvial inputs will be deposited in the river estuary and never enter Puget Sound.

2. Over 60 percent of the total inputs enter Whidbey Basin and the Southern Sound which should result in a higher sedimentation rate in these areas than in the Main Basin.

Several possible explanations for this difference were given. Since direct fluvial input to the Main Basin is small, this may indicate that the contribution from shoreline erosion is actually much larger than estimated.

-80-

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CHAPTER 5. PELAGIC BIOTA

PHYTOPLANKTON

Species Assemblages

The many species of phytoplankton observed in Puget Sound fall into three groups: the diatoms, the dinoflagellates, and the nanoflagellates. Diatoms and dinoflagellates are taxonomic divisions, while nanoflagellates are taxonomically heterogeneous; the latter grouping is based on similarities in size and evident ecological niche. The representatives of these groups appearing consistently in published reports from the Main Basin and Southern Sound are presented in Table V-1. Many of the same organisms dominate the phytoplankton communities of the Northern Sound (Phifer, 1933), Strait of Juan de Fuca (Chester et al., 1980), Strait of Georgia (Shim, 1976), Washington Coast (Postel, 1975), and open Pacific (Venrick, 1971).

Diatoms are encased in a rigid, porous silica test composed of two interlocking valves. In many diatom genera cells are linked into colonial chains, and in some of these, long siliceous spines extend from each cell. Centric diatoms possess radial symmetry, while pennate diatoms are longitudinally elongated. At any time, there are likely to be tens of diatom species present in a water sample; spring blooms, however, are numerically dominated by one to three genera of centric diatoms, most frequently Skeletonema, Chaetoceros, Thalassiosira, or Coscinodiscus (Hirota, 1967; Booth, 1969). Dinoflagellates possess two flagella; they may be naked, or armored with cellulose plates and, frequently, spines. Nanoflagellates are difficult to sample, preserve and examine due to their small size (less than 10 μm) and fragility, so less is known of their taxonomy, ecology, or abundance; a recent review is provided by Cox (1980). Both dinoflagellates and nanoflagellates are regarded by some as Protozoa. Those presented in this section possess both plant-like (chlorophyll) and animal-like (flagella) characteristics, while purely animal forms are discussed under zooplankton. The flagella of both groups provide them with limited motility; dinoflagellates can swim vertically up to 20 m per day (Eppley et al., 1968), while diatoms sink (in quiet water) at roughly 10 m per day (Parsons et al., 1977). The phenomenon of discolored water, or red tide, commonly observed in Puget Sound results from intense concentrations of dinoflagellates, or of certain animal protozoans (Quayle, 1969; Chester, 1978). Dinoflagellates are implicated in the phenomena of oyster larvae mortality (Cardwell and Woelke, 1979) and paralytic shellfish poisoning (Taylor and Seliger, 1979). An excellent treatment of general phytoplankton ecology is provided by Morris (1980).

TABLE V-1

MAJOR PHYTOPLANKTON TAXA OBSERVED IN PUGET SOUND

DIVISION CHRYSOPHYCOPHYTA, CLASS BACILLARIOPHYCEAE (DIATOMS)[a,b,d,g]

Order Centrales (Centric diatoms)

Chaetoceros debilis
C. socialis
C. laciniosus
C. decipiens
C. radicans
C. similis
C. simplex
C. densus
C. constrictus
C. didymus
C. concavicornis

Coscinodiscus wailesii
Thalassiosira aestivalis
T. decipiens
T. gravida
T. nordenskioldii
T. rotula
T. pacifica
T. eccentrica[h]
T. angstii[h]

Leptocylindrus danicus
Stephanopyxis palmeriana
Skeletonema costatum
Ditylum brightwellii

Melosira sp.
Biddulphia sp.
Rhizoselenia sp.

Order Pennales (Pennate Diatoms)

Cylindrotheca closterium
Fragilaria crotonensis
Nitzschia delicatissima
N. seriata
Thalassionema nitzschioides
Asterionella blakeleyi
Navicula sp.

TABLE V-1 (CONT'D)

MAJOR PHYTOPLANKTON TAXA OBSERVED IN PUGET SOUND

DIVISION PYRROPHYCOPHYTA (DINOFLAGELLATES)[b,c,d,e,g]

Peridinium sp.
Ceratium fusus
Gonyaulax catenella[i]
Dinophysis accuminata
Prorocentrum gracile
Amphidinium sp.

NANOFLAGELLATES (SEVERAL DIVISIONS)[f]

Cryptomonas sp.
Apedinella spinifera
Plagioselmis sp.
Hemiselmis sp.
Dicrateria sp.
Pyramimonas sp.
Chromulina sp.
Ochromonas sp.
Chrysochromulina kappa
Thalassomonas sp.
Anisomonas sp.
Distephanus speculum
Eutreptiella sp.
Rhodomonas sp.
Dichtyocha fibula

a. Gran and Angst, 1931; Cupp, 1943; Vinyard, 1975; Booth, 1969.
b. Yamaji, 1973; Smith, 1977.
c. Wailes, 1939.
d. Hirota, 1967; Thompson and Phifer, 1936; Tollefson, 1959.
e. Cummins et al., 1976; Cardwell et al., 1977 and 1979; Kruger, 1979; Krogslund, 1975.
f. No taxonomic studies of nanoflagellates in Puget Sound; references are from the Strait of Georgia: Buchanan, 1966; Stockner and Cliff, 1976; Takahashi et al., 1978; Scagel and Stein, 1961; Greve and Parsons, 1977; Thomas and Seibert, 1977; Parsons et al., 1978. Phylogeny may be found in Bold and Wynne, 1978 and Cox, 1980.
g. Phylogeny according to Bold and Wynne, 1978.
h. Formerly Coscinodiscus species (Runge, 1980).
i. Species in doubt (Turpin et al., 1978; Taylor and Seliger, 1979).

Life Cycles

Life cycles of diatoms and dinoflagellates are depicted graphically in Figure V-1. Both of the latter reproduce asexually by binary fission; in diatoms, this results in a progressive diminution of population cell size, which can be reversed only by sexual reproduction. Both groups are observed to form both temporary resting cysts and zygotes, the latter sometimes forming a more resistant overwintering cyst. Both forms of regeneration are believed to be triggered by a sudden deterioration in environmental conditions such as light intensity or nutrient concentrations; germination occurs when favorable conditions return. Cyst formation followed by overwintering in the sediments is believed to be a major strategy by which coastal phytoplankton species endure unfavorable conditions without being grazed or flushed to extinction (Werner, 1977; Taylor and Seliger, 1979). Life cycles of nanoflagellates are less studied. Asexual reproduction can sometimes occur by zoospore formation as well as by binary fission, but sexual reproduction has not been observed in all organisms and cyst formation is not widely documented (Bold and Wynne, 1978).

Temporal Changes

The dynamics of phytoplankton in the Main Basin of Puget Sound and their controlling factors, described by Campbell et al. (1977), Ebbesmeyer and Helseth (1977), and Winter et al. (1975), are summarized below.

Primary productivity and phytoplankton standing stock are principally governed by the meteorology and physical oceanography of the Sound. Vigorous upwelling at The Narrows provides a nutrient source sufficient to make surface nutrient depletion rare, while other modulating factors such as sinking, herbivore grazing, and respiration were also judged by Winter et al. (1975) to have secondary importance. The standing stock of phytoplankton observed in a water parcel at any place and time represents a biological integral of the amount of solar radiation to which the parcel is exposed during its residence at the surface of Puget Sound. The cumulative radiation absorbed, in turn, is a product of three factors: 1) the insolation at the surface, 2) the depth of water over which phytoplankton is exposed to radiation, and 3) the duration of exposure. These relationships are depicted schematically in Figure V-2.

The mean seasonal pattern of daily surface insolation was previously shown in Figure II-5 but large departures from this mean may be expected on any given day and hour. Surface insolation does not by itself limit seasonal phytoplankton production; light can be sufficient to stimulate a bloom on a sunny day even in January or February (Hood Canal: Shuman, 1978; Barlow, 1958) if other conditions are favorable.
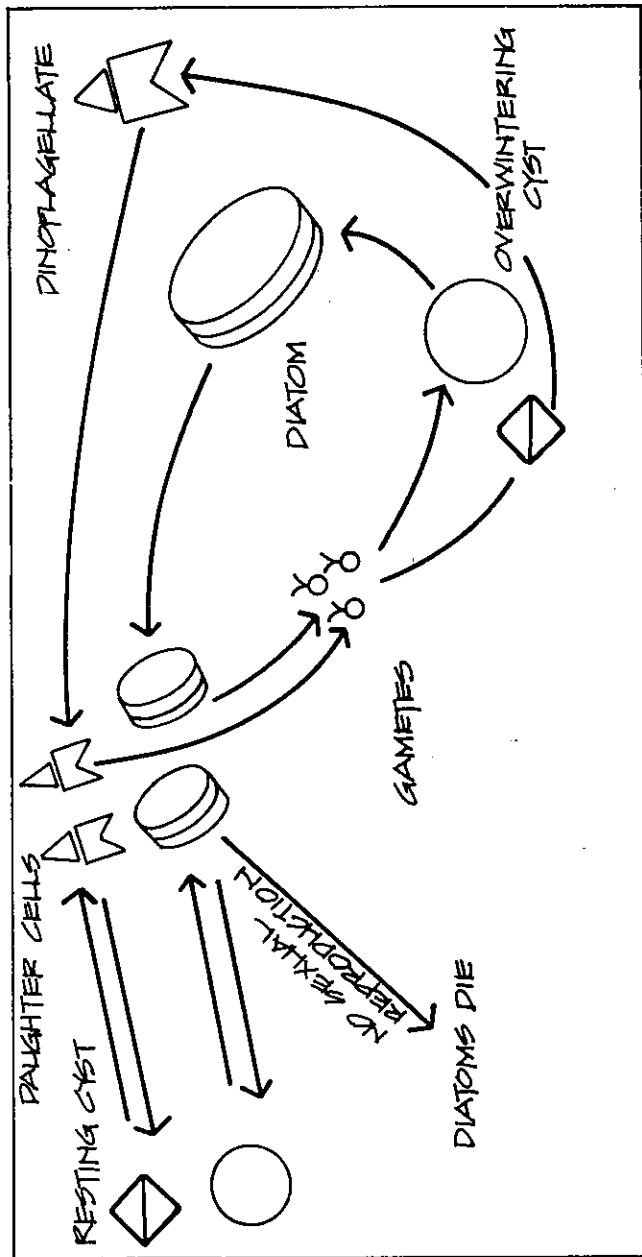
Figure V-1. Diagrams of the Life Cycles of Diatoms and Dinoflagellates.

Sources: Bold and Wynne, 1978; Davis et al., 1980; Anderson, 1980; Turpin et al., 1978; Taylor and Seliger, 1979; Werner, 1977.
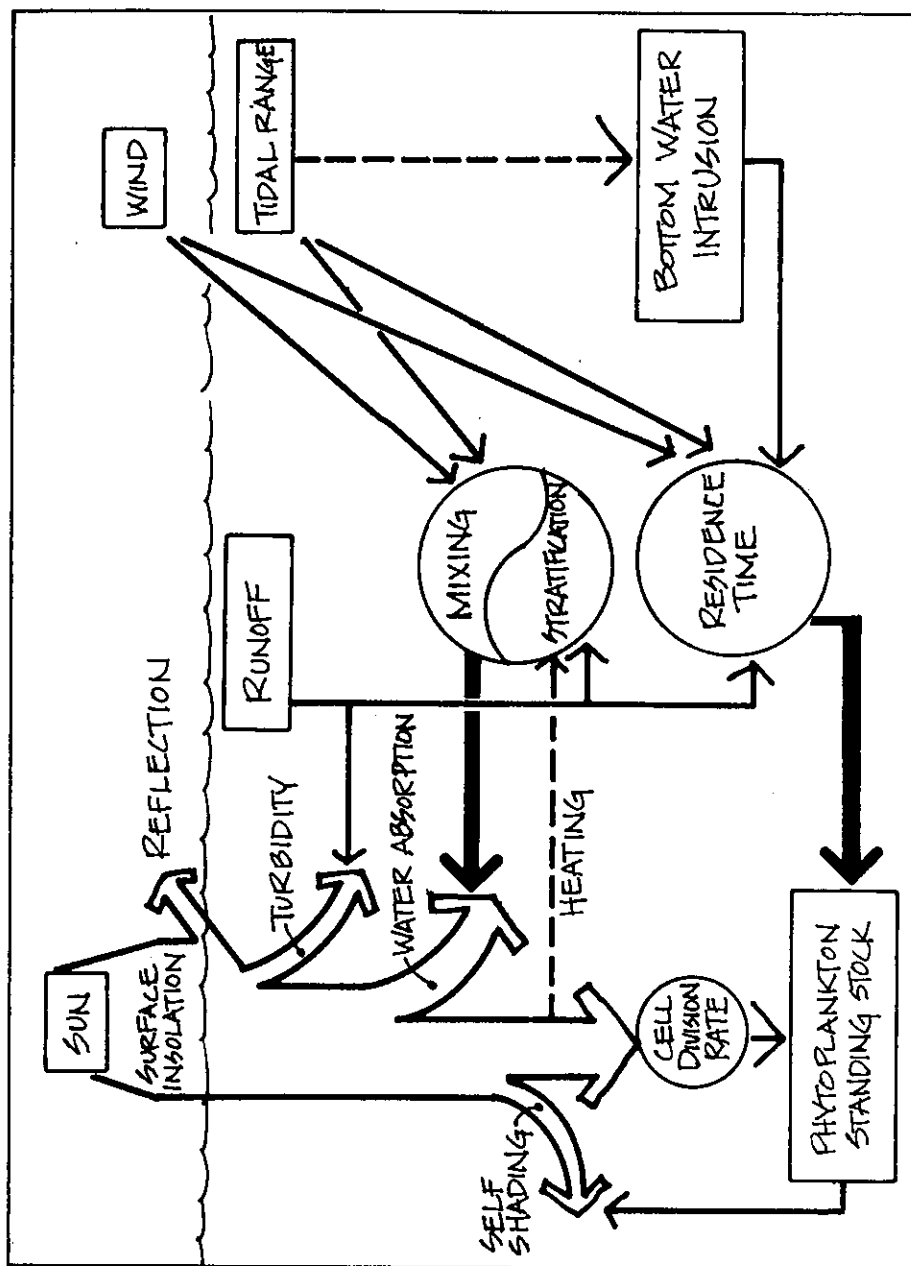
Figure V-2. Schematic Representation of the Physical Influences on Phyto-
plankton Temporal Distributions.

Sources: Campbell et al., 1977; Winter et al., 1975.

The effect of the second factor, the depth of water over which light is absorbed, is described in part by the classical Critical Depth Model of Sverdrup (1953): the greater the depth of the surface mixed layer, the smaller the fraction of surface insolation which is absorbed by phytoplankton. A spring bloom can occur when there is a sufficient increase in vertical stability and a concomitant reduction in the depth of vertical mixing. Vertical stability in Puget Sound, as reflected in the vertical density gradient (Figure III-2), is induced primarily by decreased surface salinity. Surface salinity, in turn, is a function of freshwater runoff (Figure II-7). Conditions become favorable for phytoplankton blooms in the Main Basin of Puget Sound in late April and early May - later than in most coastal areas at this latitude - when increasing density stratification in the upper 50 meters, caused by spring runoff, coincides with increasing insolation.

The degree of stratification and the depth of mixing, and hence the timing of favorable bloom conditions, are modified by surface winds, which increase mixing. Tidal range also has an influence; mixing is reduced during periods of neap tides (low tidal range) which occur in the spring at roughly two-week intervals (Figure V-3). The absorption of light within the mixed layer, furthermore, is noticeably reduced by phytoplankton self-shading and by turbidity in freshwater runoff.

The phytoplankton standing stock at a given time and place is a summation of the net algal growth rate, controlled as described above, over the period of time for which the water parcel in question has been exposed to sunlight. In the Main Basin of Puget Sound, this is a finite length of time determined by water circulation; details are discussed below, Spatial Changes. Standing stock increases proportionally to the residence time of surface water in the Main Basin (inversely proportional to flushing time). Residence time, in turn, is longer during periods of northerly winds, neap tides, low runoff, and absence of bottom water intrusion. Thus both the exact timing of the spring bloom and its subsequent fate in a given year depend on the fortuitous coincidence of sunny weather, calm or gentle northerly winds, neap tides, and strong stratification without copious runoff. A change in one of these can cause a developing bloom to stop growing, to be dispersed vertically, or to be flushed out of the basin. Favorable conditions rarely persist long enough that plant nutrients become depleted. Flushing rate was also linked to phytoplankton standing stock in enclosed marinas off the Main Basin (Cardwell et al., 1980).

Figure V-4 shows the primary productivity and phytoplankton standing stock in the Main Basin during four years in which the spring bloom was
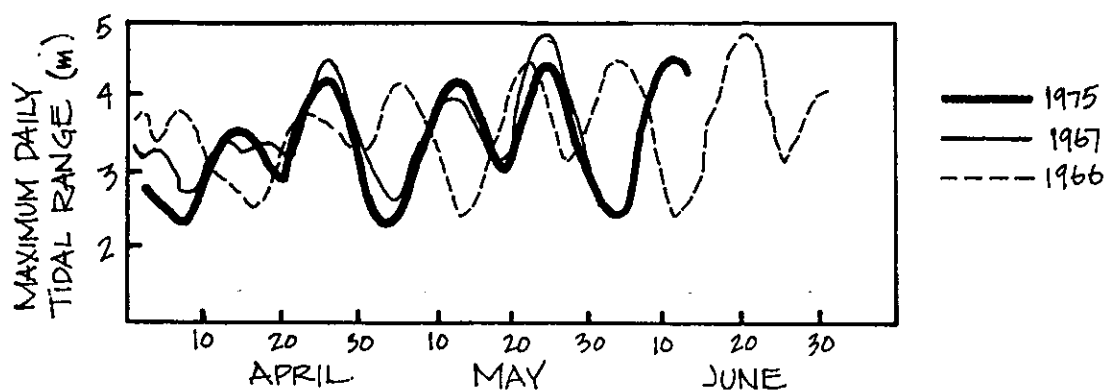
Figure V-3. Maximum Daily Tidal Ranges at Seattle During Spring 1966, 1967 and 1975.

Source: Campbell et al., 1977.
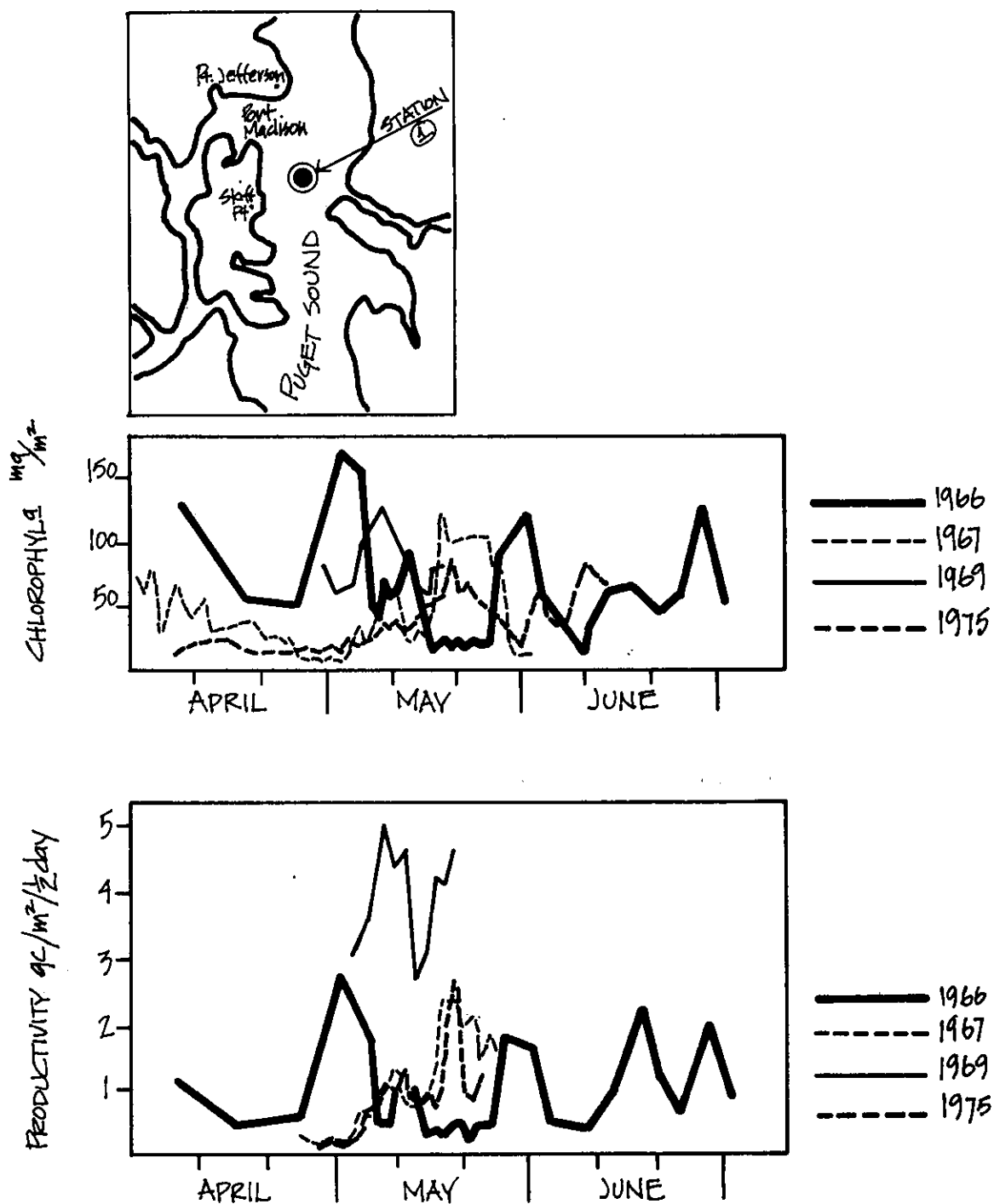
Figure V-4. Temporal Variation in Phytoplankton Productivity and in the Concentration of Chlorophyll a Observed in 1966, 1967, 1969, and 1975 at Station 1 (Main Basin).

Sources: Campbell et al., 1977; Munson, 1970.

studied intensively. It illustrates that these quantities can vary significantly on time scales of hours to days. The same is true for the species composition (Figure V-5), possibly due to both diatom life cycles (Davis et al., 1980) and spatial heterogeneity (Booth, 1969). Also apparent in Figure V-4 are differences in the timing and extent of the spring blooms of different years, due to variations in the forces described above: low productivity in 1975 due to high runoff and low sunshine, for example, contrasts with high productivity in 1969 coinciding with a neap tide, gentle northerly winds, and fair weather. Minor peaks in all years correlate well with neap tides and increased stratification (Campbell et al., 1977).

The pattern of phytoplankton abundance in the Main Basin during the rest of the year has been characterized as a series of intense blooms appearing during favorable physical conditions (Winter et al., 1975). Of the annual mean productivity of 465 $gC/m^2/yr$, roughly 86 percent occurs from April through August (Ebbesmeyer and Helseth, 1977). Seasonal patterns of standing stock in the Main Basin for several years are suggested by measurements at two to four week intervals (Figure V-6), and by the nine-year mean standing stock from monthly samples (Figure V-7). Although these are coarse sampling intervals compared to the scale of temporal variability evident from daily samples (Figures V-4 and V-5), over several years a consistent pattern emerges. This pattern of intermittent blooms, with maximal abundance in early to mid-summer, differs significantly from the classical pattern of spring and fall blooms in oceanic environments (Parsons et al., 1977). Temporal productivity of Puget Sound as controlled by circulation is compared to that of other estuaries by Sinclair et al. (1981).

No published information is available concerning the succession of phytoplankton species through the summer in the Main Basin. Reports from more stratified waters outside the study area (e.g., San Juan Channel, Thompson and Johnson, 1930; Strait of Georgia, Shim, 1976; Saanich Inlet, Takahashi et al., 1977) suggest a succession to flagellates and more southerly diatom species such as Nitzschia, but qualitative observations (B. Booth, personal communication) in the Main Basin are inconclusive. A notable member of the phytoplankton community of the Main Basin during recent summers has been the toxic red tide dinoflagellate Gonyaulax catenella, the agent of paralytic shellfish poisoning (PSP). G. catenella secretes an alkaloid neurotoxin, saxitoxin, 1000 times more potent than sodium cyanide, which accumulates in bivalves ingesting the alga (Taylor and Seliger, 1979). The shellfish may retain the toxin for months after the alga has disappeared, and may acquire toxicity from resting spores when no motile cells are present (Dale et al., 1978; Anderson, 1980). In Washington State, PSP historically has been most severe in Sequim and Discovery Bays (MacDonald, 1970), and was never recorded in Puget Sound before 1978; however, beaches throughout the Main Basin have been closed to shellfish harvest each summer since 1978. Although its growth requirements are not precisely known,
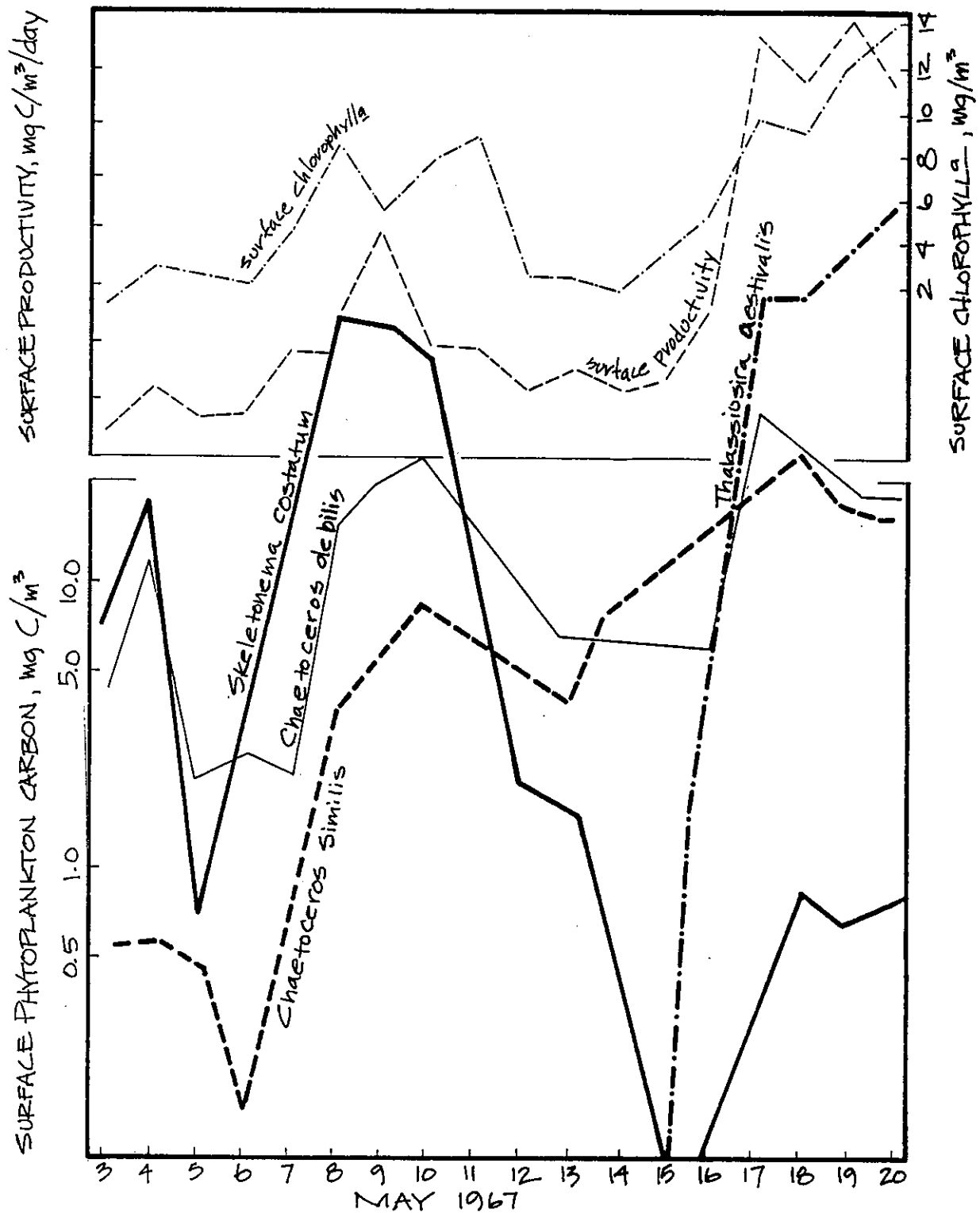
Figure V-5. Short-term Variability in the Phytoplankton Species Productivity, and Chlorophyll a Observed at Station 1 (Main Basin) in May 1967.

Source: Booth, 1969.
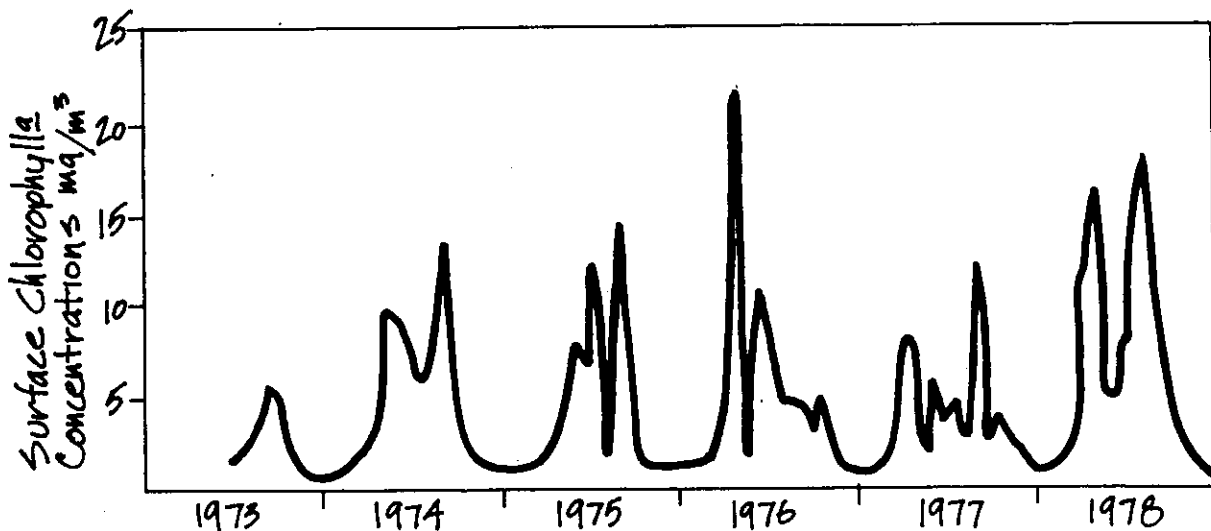
Figure V-6. Variations in the Surface Chlorophyll a Concentrations Measured Monthly off Pt. Jefferson (Main Basin) 1973 through 1978.

Source: English, 1979.
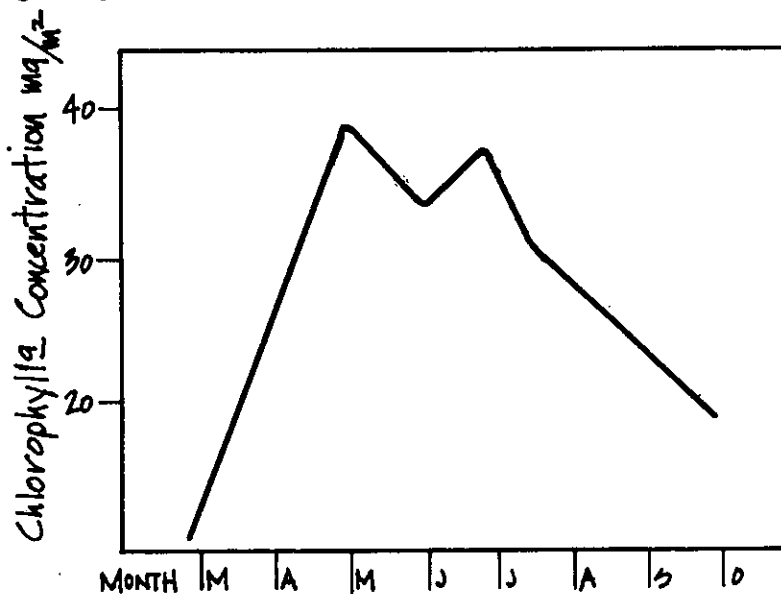
Figure V-7. Nine Year Average of the Mean Monthly Chlorophyll a Concentrations Observed at Station 1 (Main Basin) From Weekly Samples. Chlorophyll a Concentrations Were Integrated Over the Euphotic Zone. Samples Were Collected Weekly From 1966 Through 1975.

Source: Ebbesmeyer and Helseth, 1977.

G. catenella seems to thrive during sunny periods following heavy rain
(Norris and Chew, 1975), such as occurred during its first appearance in
August-September, 1978. This may be due to warm temperatures or to
stratification; Gonyaulax is hampered by turbulence (White, 1976).
There is speculation that terrestrial leachate in runoff may provide
either essential micronutrients, or organic chelators (Taylor and
Seliger, 1979; Dupuy, 1968). At present there is no explanation for the
sudden infestation, and due to the introduction of cysts into the
sediments it is unlikely to disappear.

The presence of nanoflagellates in the Main Basin has been noted
only by Hirota (1967), although they have been observed in Hood Canal
(Larrance, 1964; Shuman, 1978), in the Strait of Juan de Fuca (Chester
et al., 1980) and off the Washington coast (Postel, 1975). They cannot
be ignored in light of studies in Puget Sound (Holmes and Anderson,
1963) and elsewhere (Washington Coast - Anderson, 1965; Saanich Inlet -
Thomas et al., 1978) demonstrating that the majority of primary produc-
tion can occur among the smallest size fractions. Frequently dominant
numerically in neighboring stratified waters, nanoflagellates can also
at times compose the bulk of phytoplankton biomass despite their small
size (Takahashi et al., 1977 and 1978; Shuman, 1978).

Spatial Changes

As mentioned above, water circulation greatly affects phytoplankton
standing stock by determining the residence time of surface water within
the Main Basin. Puget Sound's Main Basin is highly productive, on a
seasonal basis, because both upwelling and stratification are present
simultaneously, but are spatially segregated. As water is advected
seaward, enrichment at The Narrows is followed by stabilization in the
open basin.

Surface water parcels originate during ebb tides principally from
upwelling and mixing at The Narrows, from advection through Colvos
Passage, and from runoff from the Puyallup and Duwamish Rivers, and the
Lake Washington Ship Canal (as well as the Whidbey Basin). Parcels
partially retain their different characters (Helseth et al., 1979) as
they are advected northward, until they are disrupted by mixing over the
sill at Admiralty Inlet. The transit from The Narrows to Admiralty
Inlet is believed to take an average of six days (Ebbesmeyer and Helseth,
1977), with parcels moving seaward roughly nine kilometers with each
tidal cycle (Munson, 1970).

Phytoplankton standing stock and productivity levels are highest
within the surface euphotic zone, the depth of which varies seasonally
between 10 and 50 meters. Peak abundance can sometimes occur slightly

below the surface (e.g., Hirota, 1967; Munson, 1970), but in the Main Basin no deep chlorophyll maximum has been observed, as found off the Washington coast (Postel, 1975) or in Dabob Bay (Shuman, 1978). Nevertheless, a significant standing stock of viable phytoplankton (>2 μg chlorophyll-a per liter) is found in the aphotic zone; vertically integrated, this aphotic chlorophyll exceeds that in the euphotic zone (Winter et al., 1975). Feedback of upper layer water from Admiralty Inlet toward The Narrows via this lower layer causes an increase in chlorophyll and a decrease in nutrients at depth over the summer. Recycling and upwelling of this lower layer water may provide a seeding mechanism for phytoplankton blooms similar to that suggested in Chesapeake Bay by Tyler and Seliger (1978).

Phytoplankton standing stock is highly heterogeneous, or "patchy," in both the horizontal and vertical dimensions. Surface patchiness is illustrated by continuous chlorophyll surveys (Figure V-8). No attempt has been made to correlate biological and physical patchiness in Puget Sound, as done in the Strait of Georgia by Wiegand and Pond (1979). Ebbesmeyer and Helseth (1977), however, found no significant systematic differences in mean productivity between different stations in the Main Basin. Preliminary results suggest that patchiness may influence species composition (Turpin and Harrison, 1979 and 1980), and Booth (1969) associated different diatom species with different water masses in the Main Basin. Thompson and Phifer (1936) provided the only rapid survey of phytoplankton species differences throughout the Sound, and the only documentation of dinoflagellate dominance in the Main Basin.

Worldwide, large centric diatoms are the dominant phytoplankters in waters of strong mixing or upwelling, which supply adequate nutrients and retard sinking (Blasco et al., 1980; Garrison, 1979; Pingree et al., 1978). The rate of upwelling can influence species composition, as demonstrated experimentally by Thomas et al. (1980) and Grice et al. (1980). When both groups are grown under their respective optimal conditions, diatoms can grow faster than flagellates - two to three generations per day versus one - and hence have an overall competitive advantage (Chan, 1978; Thomas et al., 1978). A recent hypothetical scheme of the conditions of moderate nitrogen concentrations and light intensities under which diatoms can realize this advantage and dominate locally is depicted in Figure V-9. Supporting experimental data are provided by Harrison and Davis (1979). Grice et al. (1980) and Officer and Ryther (1980) document silicate limitation of diatoms in enclosures in Saanich Inlet, but there have been no such local observations in the wild.

Flagellates are associated with poorly mixed, stratified, and often nutrient-depleted waters, with slower upwelling (Blasco, 1977;
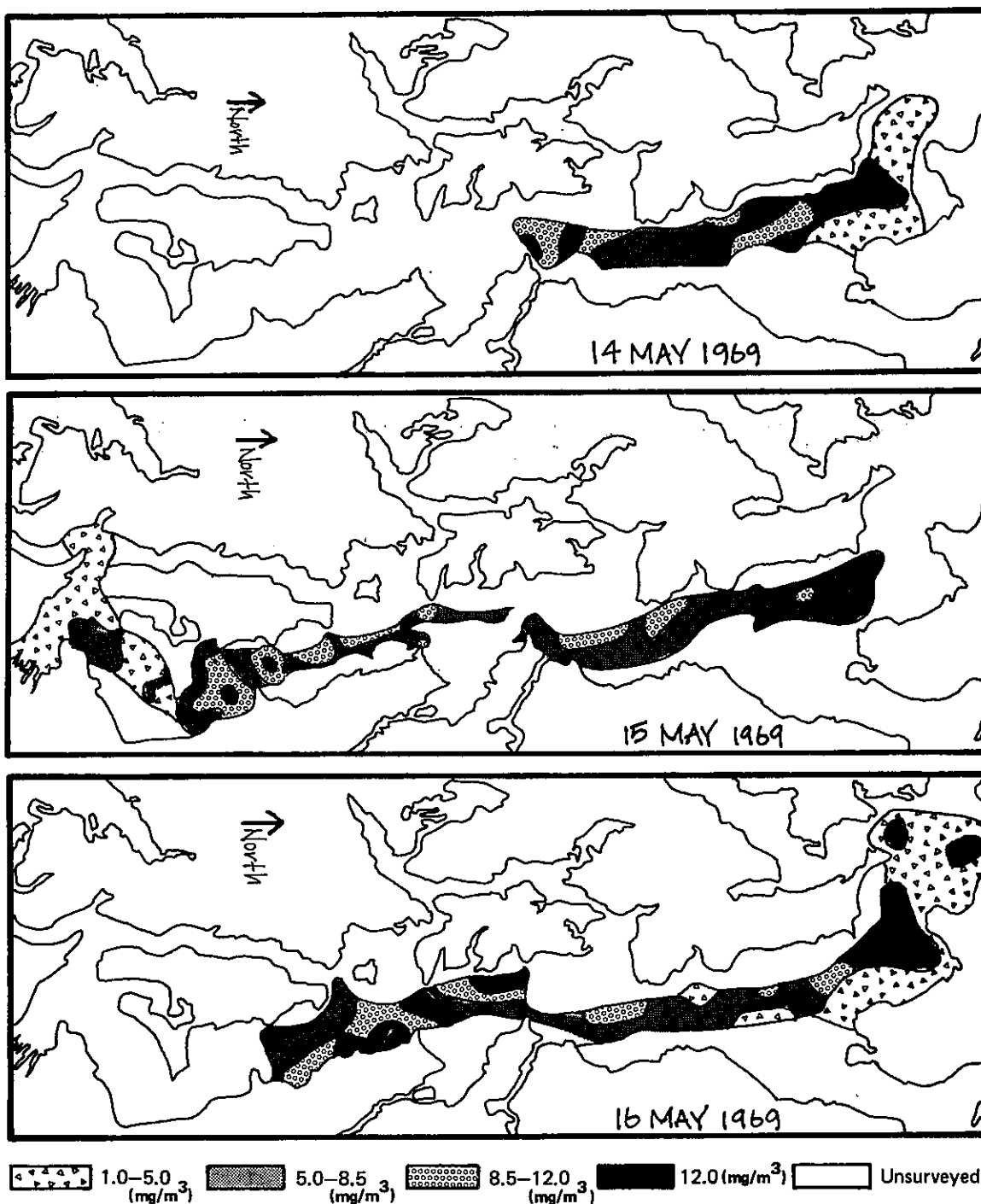
Figure V-8. Spatial Variability in the Concentrations of Chlorophyll a in the Main Basin During May 1969.

Source: Munson, 1970.
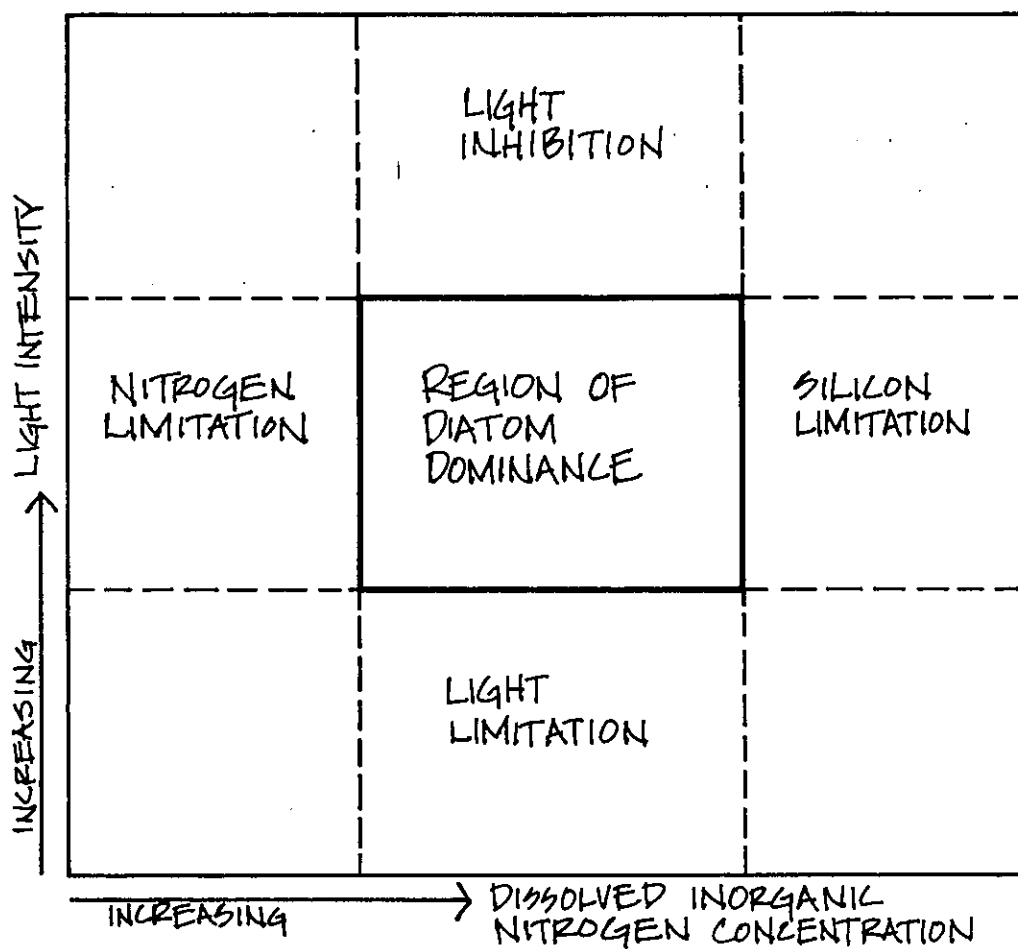
Figure V-9. Proposed Relationship Between Light Levels and Dissolved Inorganic Nitrogen Concentrations Required for the Productivity Dominance of Diatoms Over Flagellates.

Source: Parsons et al., 1978.

Pingree et al., 1978; Grice et al., 1980). They are also shown to prefer warmer water, Gymnodinium splendens achieving maximal growth at 20-25°C (Thomas et al., 1973) versus 15-20°C in Skeletonema (Jitts et al., 1964). Their migratory ability enables them to avoid sinking from the surface in calm, stratified water, and possibly to escape predation and utilize subsurface nutrients at night (Eppley et al., 1968). Motile flagellates may also be able to seek a depth of optimal light intensity and so persist where it is too bright or dim for nonmotile diatoms. A complex analysis of the hydrographic conditions favoring dinoflagellate growth is being developed by Margalef (in Taylor and Seliger, 1979).

Data on the relative abundance of dinoflagellates throughout Puget Sound are sketchy. However, the incidence of oyster larvae mortality is particularly associated with the presence of certain dinoflagellates (Cardwell et al., 1979). Figure V-10 shows the spatial incidence of oyster larvae mortality in Puget Sound as the best available indication of the spatial occurrence of dinoflagellates. These data suggest that dinoflagellates are uncommon in the Main Basin and more abundant in the Southern Sound and embayments. Other agents such as low salinity and pollution are also implicated in oyster larvae mortality, however, and strict correlations between dinoflagellate numbers and mortalities have not been observed.

Embayments

Elliott Bay. The few data available show the same phytoplankton species in Elliott Bay as in the Main Basin (Krogslund, 1975). Annual productivity, however, is significantly lower due to turbidity contributed by the Duwamish River estuary (Ebbesmeyer and Helseth, 1977).

Duwamish River Estuary. The dynamics of phytoplankton in the Duwamish River estuary have been reported by Santos and Stoner (1972) and Welch et al. (1972).

The factors controlling blooms in the estuary are the same as those in the Main Basin: blooms coincide with periods of long retention time caused by low runoff and low tidal range, and with increased stratification, which, unlike that of the Main Basin, is thermally induced. Blooms do not appear until the low-flow season in August, and in some years no bloom is observed (Welch and Trial, 1979).

Productivity of Duwamish estuary phytoplankton is not limited by nutrients, and the Duwamish is a significant source of nutrients (particularly nitrogen) to Elliott Bay. Standing stock of chlorophyll at the estuary surface can greatly exceed that observed in the bay or the open basin (up to 90 mg/m^3), so during blooms the estuary is also a source of phytoplankton to the bay. The blooms are dominated by the same centric diatoms (e.g., Skeletonema and Thalassiosira) found in the
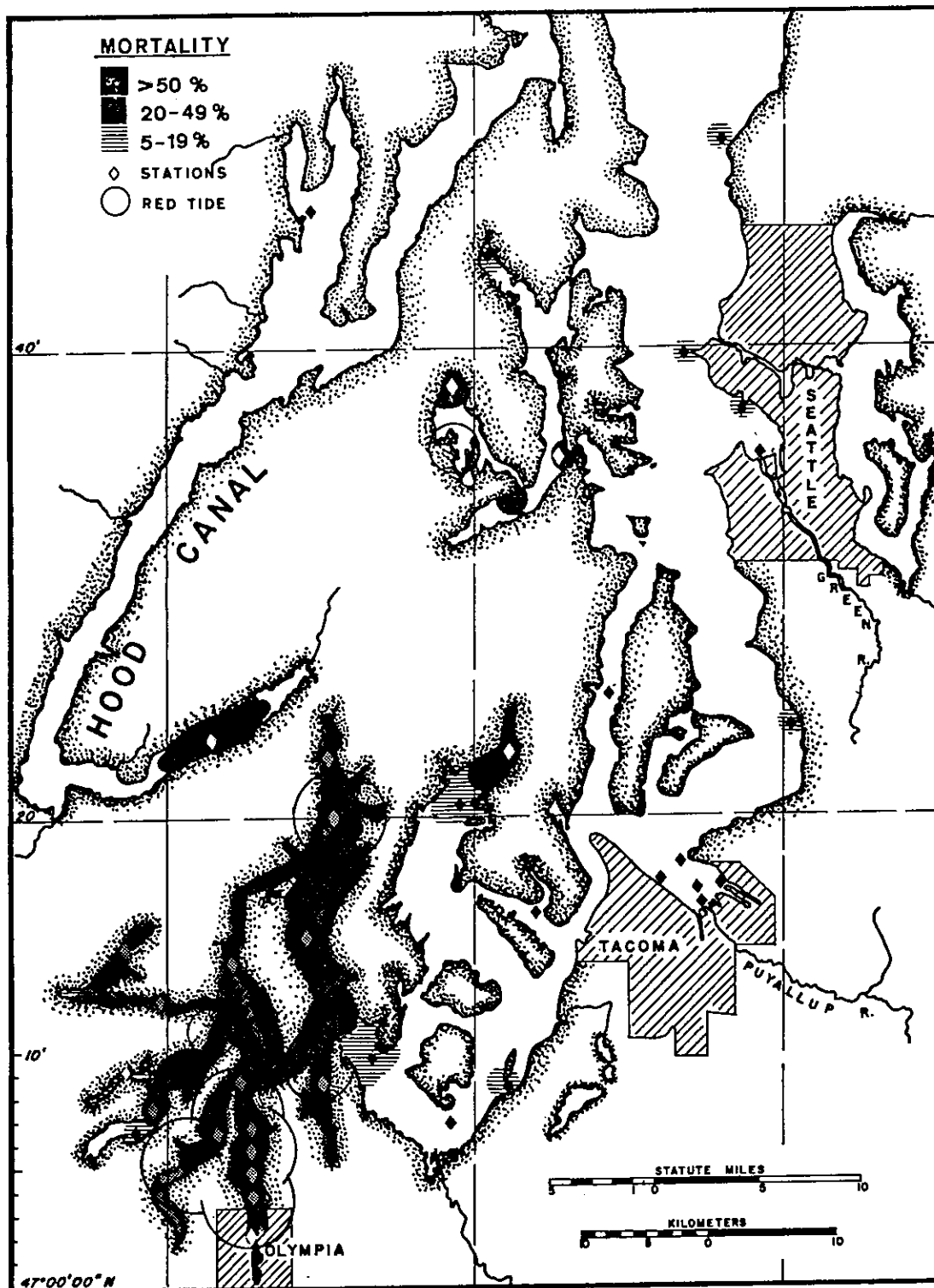
Figure V-10. Distribution of Oyster Larvae Toxicity and Red Tides in Puget
Sound, 1977.

Source: Cardwell et al., 1979.

Main Basin, but during non-bloom conditions standing stock is low and composed of freshwater species. Productivity during blooms is comparable to the highest levels observed in the Main Basin. Maximal standing stock during blooms at low tide occurs between 8 and 10 km upstream from the mouth, and at a depth of about 1 m. Decomposition of bloom biomass which sinks to the river bottom causes oxygen depletion and nutrient enrichment, both of which contribute to water quality problems in the estuary.

Commencement Bay. The few data available on Commencement Bay phytoplankton (Pavlou et al., 1973) indicate that the Port of Tacoma waterways can be sources of dissolved nitrogen and of chlorophyll to the bay. Waters from some locations in Commencement and Elliott Bays, as well as in the Main Basin, have demonstrated oyster larval mortality (Cardwell and Woelke, 1979). The presence of red tide dinoflagellates often associated with such mortalities has not been confirmed in these locations; however, and pollution and low salinity are also likely causes (Cardwell et al., 1977).

Southern Sound. Fewer data are available on phytoplankton from the Southern Sound than from the Main Basin. The most comprehensive study (G. C. Anderson, unpublished), at the mouth of Case Inlet, found that primary productivity began increasing in February and March, well before the spring blooms in the Main Basin (Figure V-11). This was attributed to shallower water limiting the depth to which mixing could occur. Similar results were obtained at the head of Hood Canal (Lynch Cove) by Barlow (1958). Productivity through the summer was more continuous, but lower, than that in the Main Basin; mean annual productivity was 270 gC/m^2/yr, 60 percent of that in the Main Basin. This was attributed to lower stability and stronger mixing caused by a minor sill at the mouth of this inlet (Figure V-11).

Higher standing stock of phytoplankton (30 mg chlorophyll-a/m^3) has been observed in Budd Inlet (Kruger, 1979) and Henderson Inlet (Pease, 1977; Rensel, 1976) than at the mouth of Case Inlet, which is the source of sea water for both inlets. Both also experience some surface nutrient depletion, and Budd Inlet experiences oxygen depletion due to decay of phytoplankton near the bottom. Low nutrient concentrations and high temperatures in summer are characteristic of surface waters at the heads of Carr Inlet (Collias et al., 1974), and Hammersley and Totten Inlets (Olcay, 1959). Monthly samples suggest lower phytoplankton standing stock during summer in Carr Inlet than in the Main Basin (Figure V-12). Although the subject has not been studied directly, these data are consistent with the hypothesis that weaker mixing and longer residence times in Carr Inlet allow surface nutrient depletion to occur during summer and thus reduce annual
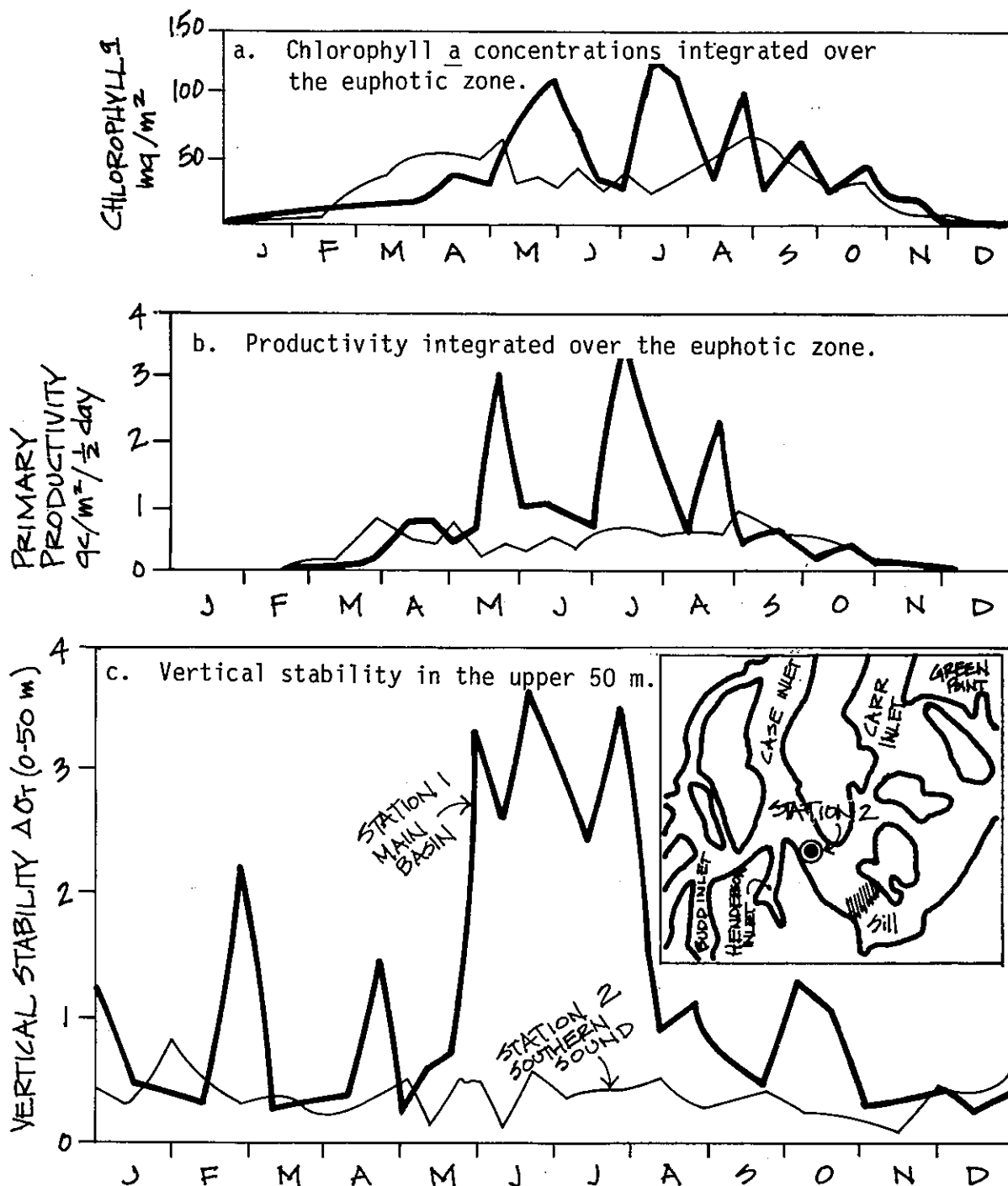
Figure V-11. Comparisons of the Temporal Variations in the Chlorophyll a, Productivity and Vertical Stability Observed at Station 1 (Main Basin), and Station 2 (Southern Sound), in 1964.

Source: G. C. Anderson, Department of Oceanography, University of Washington, unpublished data.
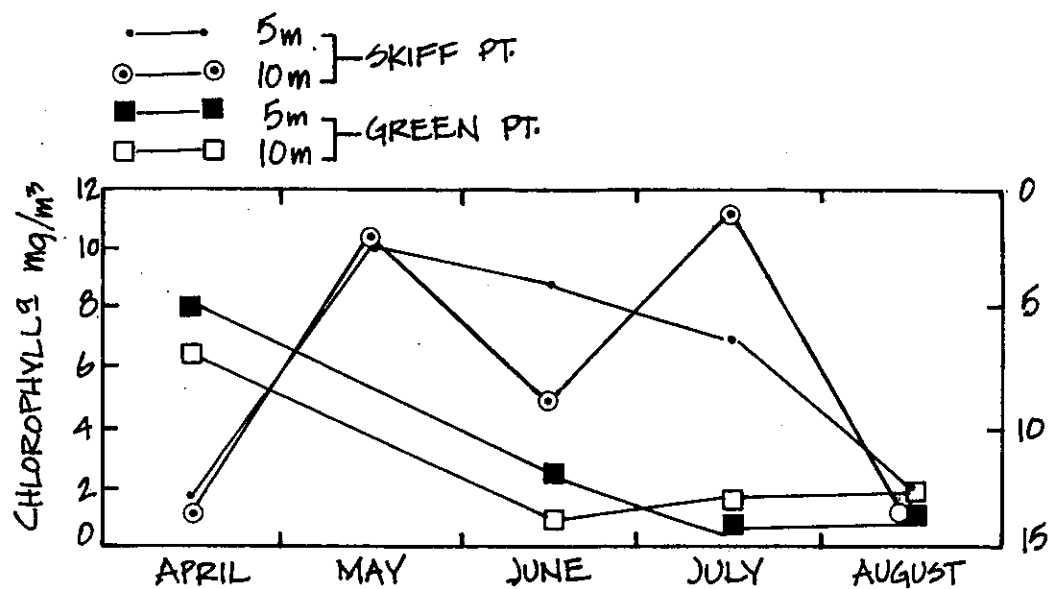
Figure V-12. Chlorophyll a Concentrations Observed Off Skiff Point (Main
   Basin) and Green Point (Carr Inlet, Southern Sound) Spring and Summer
   1969.

Source: Cooney, 1971.

productivity, as observed in Dabob Bay by Shuman (1978) and Larrance (1964). Such a situation might be inferred in other Southern Sound inlets as well.

In the Southern Sound, the armored dinoflagellate, Ceratium fusus, and the unarmored Gymnodinium splendens are associated with severe mortality in larval and adult oysters, larval clams and shrimp, and juvenile salmon (Cardwell et al., 1977 and 1979; Cardwell and Woelke, 1979; Rensel, 1976). Unlike many chemical pollutants, these algae seem to cause mortality without inducing larval abnormalities at lower concentrations. Ceratium is thought to physically damage animals with its long spines. The mode of toxicity by Gymnodinium is unknown but is possibly chemical. As shown in Figure V-10, Southern Puget Sound has a higher incidence of oyster larvae mortality which suggests that dinoflagellates may be more prevalent in this area.

The pattern and intensity of mortality vary from year to year. Mortality typically extends from June to November, peaking between August and October. C. fusus and G. splendens, and the associated mortality, are most common in shallow, poorly flushed, stratified inlets, and often below the surface; well-mixed channels and deep waters have reduced or zero toxicity. The three locations measured in 1977 with highest oyster larvae mortality (Cardwell et al., 1979) were all in Budd Inlet.

Little information exists on diatom populations in the Southern Sound, although data of Tollefson (1959) show shifts from the typical spring diatom community to a summer dinoflagellate assemblage in both Oakland Bay (Hammersley Inlet) and Oyster Bay (Totten Inlet) in 1957 and 1958.

Sinclair Inlet and the Port Orchard System. The inlets of the Port Orchard system, like those in the Southern Sound, are relatively warm, shallow and poorly flushed. The few data available on phytoplankton in this area are similar to those of the Southern Sound. Krogslund (1975) observed a subsurface bloom of Gymnodinium off the head of Sinclair Inlet in November 1973 when low diatom populations inhabited the Main Basin and Elliott Bay.

Sinclair Inlet, Dyes Inlet, and Liberty Bay also have been subject to oyster larval mortality (Figure V-10). Cummins et al. (1976) associated toxicity to oyster embryos in Liberty Bay in September 1975 with the presence of Prorocentrum gracile as well as of Gymnodinium splendens, although toxicity was mostly strongly correlated with total organic carbon.

ZOOPLANKTON

Species Assemblage

Comparable to the phytoplankton, many different taxa of zooplankton have been observed in Puget Sound. However, the zooplankton is a far more taxonomically diverse group than the phytoplankton; between the holoplankton (animals which are planktonic their entire lives) and the meroplankton (planktonic larvae of nonplanktonic adults such as benthos and fish), it includes representatives of nearly every animal phylum. This section considers primarily the holoplankton, with meroplankton included under benthic fauna in the following chapter.

Zooplankton species are separated operationally by size into three groups: 1) microzooplankton, which are unicellular (except for rotifers) and so small that they must be sampled with bottles rather than nets; 2) mesozooplankton (also called net zooplankton) captured by nets with mesh sizes of at least 200 micrometers; and 3) micronekton, which can avoid smaller nets and must be sampled using trawls of mesh size 12.5 millimeters or greater (UNESCO, 1968). These size categories can be used to indicate the feeding habits and predators of these animals.

At the present time, only limited data are available in this region for most of these zooplankton groups. Those organisms appearing consistently in published reports from the Sound area are presented in Table V-2, which illustrates the complexity and richness of the zooplankton community. These organisms are considered typical of Pacific coastal waters, and have been observed in the Strait of Georgia (Gardner, 1977), the Strait of Juan de Fuca (Chester et al., 1980), the San Juan Islands (Johnson, 1932), Washington-Oregon coasts (Peterson and Miller, 1977; Peterson, 1972), and the North Pacific (Takenouti, 1972; McGowan, 1971). Specific discussions of Puget Sound zooplankton in relation to the Pacific community are provided by Frost (1974), Damkaer (1964), Hebard (1956), and references therein.

Data from the only two published surveys indicate that mesozooplanktonic copepods dominate the zooplankton of the Main Basin. Hebard (1956) found the small copepods Corycaeus (a carnivore) and Pseudocalanus and Microcalanus (herbivores) numerically dominant. The most numerous micronekton group was the amphipods, but Hebard's use of daytime samples and small nets probably underestimates micronekton abundance. Cooney (1971) found that copepods, principally the larger herbivore Calanus, contributed up to 80 percent of the mesozooplankton and micronekton biomass; up to 40 percent was contributed by euphausiids (principally E. pacifica) and amphipods (principally P. pacifica). These data demonstrate the predominance of crustaceans in the zooplankton. Hebard (1956) found crustacean larvae, notably those of barnacles and brachyuran crabs, among the dominant meroplankton. The crustaceans also are the best studied zooplankton group on the Sound.

TABLE V-2

MAJOR ZOOPLANKTON TAXA OBSERVED IN PUGET SOUND

Phylogeny is according to Smith and Carlson (1975). Dominant genera or species within a size class are preceded by *, while superscript letters refer to references at end of table.

MICROZOOPLANKTON[z]

Phylum Protozoa[k,l,m]
  Dinoflagellates
    Noctiluca miliaris[j,n] (= N. scintillans)

Ciliates[u]

  Holotrich
    Mesodinium rubrum
    Tiarina fusus
    Didinium nasutum

  Oligotrich
    * Strombidium (13 species)
    * Lohmaniella (2 species)

  Tintinnid[i,n,p]
    * Tintinnopsis (8 species)
    * Stenosemella (2 species)
    Eutintinnus (5 species)
    Favella franciscana
    Parafavella gigantea
    Helicostomella subulata

Flagellates[e]
  Monas sp.
  Bodo sp.
  Oikomonas sp.

Foraminifera[w]
  Globigerina sp.

Radiolaria[k,e]
  Lithomelissa setosa

Phylum Rotifera[k,l,n]
  Trichocera marina
  Synchaeta sp.

MESOZOOPLANKTON

Phylum Arthropoda, Class Crustacea

  Subclass Copepoda[a,b,c,d,h,i,j,l,n,u,v]

    Order Calanoida
      * Calanus pacificus
        Calanus sp.
      * Pseudocalanus minutus
        Pseudocalanus elongatus
      * Acartia longiremis
        Acartia clausi
      * Microcalanus pusillus
        Paracalanus parvus
        Aetidius armatus
        Epilabidocera amphitrites
        Tortanus discaudatus
        Metridia lucens
        Candacia columbiae
        Microsetella rosea
        Euchaeta japonica (= Paraeuchaeta elongata)

    Order Cyclopoida
      * Corycaeus affinis
        Oithona similis
        Oithona sp.

    Subclass Cladocera[a,d]
      Evadne nordmanni
      Podon leuckarti

    Subclass Ostracoda[e,x]
      Conchoecia sp.

Phylum Chaetognatha

  Sagitta elegans[d,h,i,q,u]

Phylum Ctenophora[h,u]

      Pleurobrachia pileus
      Bolinopsis sp.

Phylum Cnidaria[i,l,t]

  Class Hydrozoa
      Phialidium gregarium
      Aequorea sp.
      Sarsia sp.
      Stomotoca sp.

MESOZOOPLANKTON continued

  Class Hydrozoa continued
      Obelia sp.
      Halistaura sp.
      Gonionemus sp.

Phylum Mollusca

  Class Gastropoda (Pteropods)[o,v]
      Clione kincaidi
      Limacina sp.

Phylum Chordata, Subphylum Urochordata (Tunicates)[d,f,i,l,n,u]

  Class Larvacea
      Oikopleura dioica
      Oikopleura labradorensis
      Fritillaria sp.

MICRONEKTON[z]

Phylum Arthropoda, Class Crustacea

  Subclass Decapoda
      Pasiphaea pacifica[f,h]

  Order Euphausiacea[d,h,i,s]
    * Euphausia pacifica
    * Thysanoessa raschii
    * T. longipes
    * T. spinifera

  Order Mysidacea[g,h,s]
    * Neomysis kadiakensis
    * N. rayii
    * Acanthromysis macropsis
      A. nephrophthalma
      A. pseudomacropsis
      Holmesiella anomala

  Order Amphipoda, Suborder Hyperiidea[a,d,h,i,r]
    * Calliopius laeviusculus
    * Cyphocaris challengeri
    * Parathemisto pacifica
      Euprimno sp.

Phylum Annelida, Class Polychaeta[y]

      Tomopteris sp.
      Odontosyllis sp.

TABLE V-2 (CONT'D)

REFERENCES

a. Hebard (1956), Main Basin
b. Davis (1949), Main Basin
c. Frost (1974), Main Basin
d. Aron (1958), Main Basin
e. Lighthart (1969), Main Basin
f. Galt (1970), Main Basin
g. Thorne (1968), Main Basin
h. Cooney (1971), Main Basin
i. Dempster (1938), Hood Canal
j. Damkaer (1964), Hood Canal; Fulton (1972), Strait of Georgia;
   Johnson (1934a and 1934b), San Juan
k. Chester (1978), Strait of Juan de Fuca
l. Chester et al. (1980), Strait of Juan de Fuca
m. Wailes (1937, 1943), Strait of Georgia
n. Thompson and Johnson (1930); Johnson (1932), San Juan
o. Agersborg (1923), San Juan
p. Thompson (1936), Hood Canal
q. King (1979), Hood Canal
r. Thorsteinson (1941), Strait of Georgia
s. Banner (1947, 1948, 1950), North Pacific
t. Arai (1973); Arai and Brinckmann-Voss (1980), Strait of Georgia;
   Strong (1925); Gellerman (1926), San Juan
u. Grice et al. (1980); Reeve (1980), Strait of Georgia
v. Gardner (1977), Strait of Georgia
w. Smith (1963); Cockbain (1963), Strait Juan de Fuca
x. McHardy and Bary (1965), Strait of Georgia
y. Berkeley (1930), Strait of Georgia
z. Smith (1977); Yamaji (1973)

There have been no systematic studies of microzooplankton in Puget Sound. Chester (1978) studied the microzooplankton of the Strait of Juan de Fuca, which was dominated by the oligotrich and tintinnid ciliates. Rotifera, Foraminifera, and Radiolaria were uncommon. Little is known about flagellates. The microzooplankton includes some plant-like forms: the heterotrophic dinoflagellate Noctiluca, and Mesodinium rubrum which contains photosynthetic endosymbiotic algae (Chester, 1978) and may be autotrophic. Each of the latter organisms can form intense non-toxic red tides during summer, but at other times they are scarce. Despite high numerical abundance, seasonally microzooplankton was not a significant fraction to total zooplankton biomass in the Straits of Juan de Fuca (Chester et al., 1980) and Georgia (Parsons et al., 1970). The latter stressed, however, that this may underestimate microzooplankton importance to the food web.

Similar to the red-tide organisms in their "boom-or-bust" abundance pattern are the gelatinous ctenophores and cnidarians, which can form dense surface windrows or be virtually absent. There is little documentation of their appearances within the study area. Hebard's (1956) data indicate that the gelatinous chaetognaths have more consistent and moderate populations, as do the pteropods and larvaceans; annelids, cladocerans and ostracods are uncommon.

Life Cycles

In keeping with their great taxonomic diversity, the life cycles of different zooplankton groups vary widely. Reproduction may be either asexual or sexual, although the former is limited to the Protozoa and Cnidaria. Development may be direct, with juveniles identical to adults except in size, or indirect, with juveniles passing through one or more dissimilar stages of maturity. These differences are summarized in Table V-3, together with available references to specific local organisms.

Zooplankton species undergoing indirect development, crustacean zooplankton in particular, undergo dramatic changes in size and morphology during immaturity. The larger and more advanced the species, in general, the more numerous the intermediate stages before adulthood, each stage having a slightly different ecological niche. The rate of zooplankton production, a function of egg-laying and of developmental rates, depends on both food supply and temperature. Larger and more advanced animals, as a general rule, also have longer life spans, graphically summarized in Figure V-13. These range from a few days among microzooplankton to up to 2 years among micronekton. Although a rigorous evaluation has not been performed, Figure V-13 compares favorably with the classical logarithmic dependence of animal metabolic rate on body size (e.g., Banse and Mosher, 1980). The frequency of variability in numerical abundance of a species is linked to its size via its reproductive rate.

TABLE V-3

ZOOPLANKTON LIFE CYCLES

ORGANISM	DOMINANT TYPE OF REPRODUCTION	DEVELOPMENT	REFERENCES
MICROZOOPLANKTON			
Ciliates	asexual	direct	
Tintinnids			Blackbourn (1974)
Flagellates	asexual	direct	Dewey (1976);
Noctiluca			Zingmark (1970)
Rotifers	sexual	direct	Dewey (1976)
MESOZOOPLANKTON			
Crustaceans	sexual	indirect	
Copepods			McLaren (1978)
Calanus			Marshall and Orr (1972);
			Vidal (1978)
Pseudocalanus			Corkett and McLaren (1978)
Paracalanus			Checkley (1980)
Acartia			Landry (1978)
Tortanus			Johnson (1934a)
Epilabidocera			Park (1965); Johnson (1934b)
Corycaeus			Wootton (1943); Gibson and
			Grice (1978)
Cladocerans			Onbe (1978)
Chaetognaths	sexual (hermaphroditic)	direct	King (1979)
Ctenophores	sexual (hermaphroditic)	direct	Reeve and Walter (1978); Reeve (1980)
Cnidarians	both (hermaphroditic)	direct (alternation of generations)	Huntley and Hobson (1978)
Molluscs			
Pteropods	sexual	indirect	Conover and Lalli (1974); Lalli (1967)
Chordates			
Larvaceans	sexual	indirect	Alldredge (1976); Galt (1970 and 1972)
MICRONEKTON			
Crustaceans	sexual	indirect	
Euphausiids			Ross (1979); Mauchline (1980);
Mysids			Wittman (1978);
Amphipods			Dagg (1975)
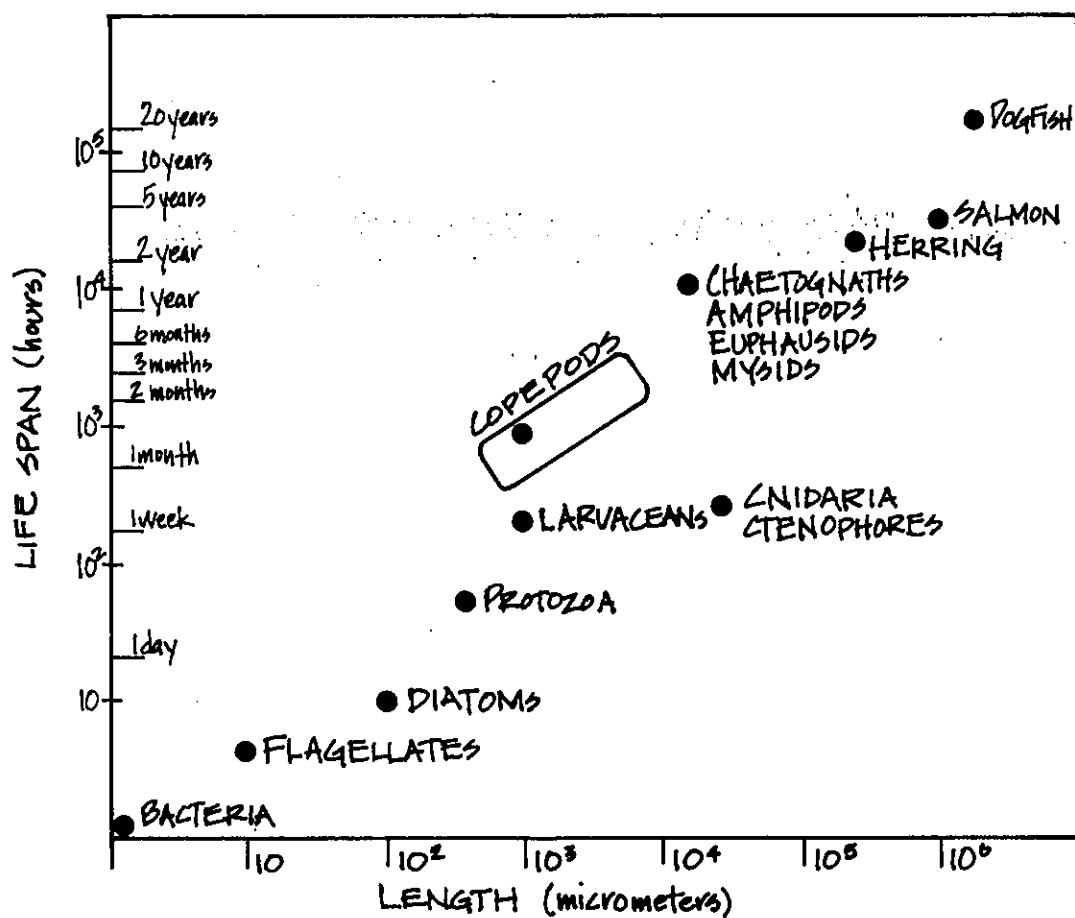
Figure V-13. Approximate Life Span Versus Approximate Adult Size of Common Puget Sound Pelagic Organisms.

Source: See Tables V-1 and V-2.

Temporal Changes

Despite the greater complexity and diversity of the zooplankton
community of Puget Sound, fewer data are available about it than
about the phytoplankton. No information at all is available on micro-
zooplankton within Puget Sound. Dempster (1938) and Chester (1978)
found peak abundance of microzooplankton during summer and fall in Hood
Canal and the Strait of Juan de Fuca, respectively, and document some
changes in species composition. Chester (1978) and Takahashi et al.,
(1978) found that microzooplankton abundance closely paralleled phyto-
plankton standing stock, particularly that of nanoflagellates, in
accordance with the short generation times of Protozoa. Red-tide blooms
of Noctiluca were observed during summer and fall in all three studies;
Mesodinium blooms were observed during summer in the Strait of Juan de
Fuca and during winter in Saanich Inlet.

Hebard (1956) inventoried the mesoplankton and micronekton of the
Main Basin on a seasonal basis; abundances of three numerically dominant
genera are presented in Figures V-14 and V-15. Total zooplankton
biomass was highest from May through September. Although simultaneous
phytoplankton studies were not conducted, the 1955 peaks show a lag of
roughly one month behind the mean seasonal pattern of phytoplankton
standing stock (Figure V-7), consistent with the generation times of
copepods. A major problem in making such determinations is variability
in measurements; Hebard (1956) noted that surface zooplankton standing
stock at a single station could vary fourfold over a 24-hour period,
primarily due to spatial heterogenity (see below).

The temporal abundances of those mesozooplankton taxa with anomalously
short generation times - the ctenophores, cnidarians and larvaceans -
are characterized by rapid appearances and disappearances. Examples are
provided by Galt (1970) and Huntley and Hobson (1978). Temporal abundances
of meroplanktonic larvae are presented under Benthos, below.

Data on the seasonal abundance of micronekton, as represented by
Euphausia pacifica, are presented in Figure V-16. Maximal standing
stock occurs in the spring and summer, consistent with the life cycle of
E. pacifica, which produces only one cohort of young each spring in the
Main Basin (Hulsizer, 1972). In contrast, spawning by copepods continues
throughout the year, with juveniles (nauplii and copepodites) generated
and present in large numbers throughout the summer (Hebard, 1956).
Cyclic fluctuations in micronekton abundance related to food supply have
not been examined, but most likely would be visible only by comparing
consecutive year-classes.
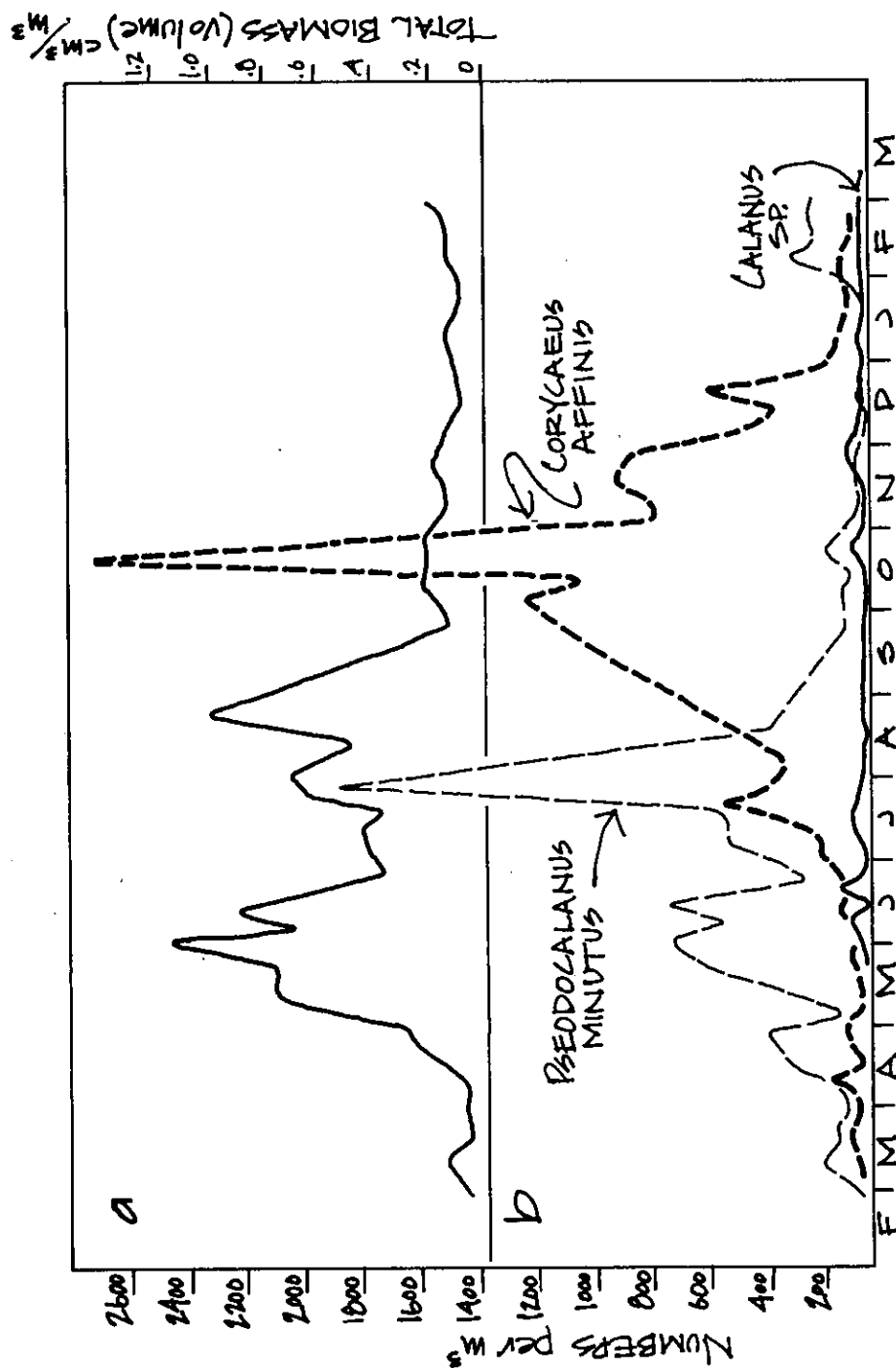
Figure V-14. Seasonal Biomass of Total Zooplankton (a) and Numerical Abundances of Major Copepods (b) in Surface Waters (0-57 meters) of the Main Basin, 1955 to 1956. Samples were collected weekly off Pt. Jefferson.

Source: Hebard, 1956.

Figure V-15. Seasonal Biomass of Total Zooplankton (a) and Numerical Abundances of Major Copepods (b) in Deep Waters (57-148 meters) of the Main Basin, 1955 to 1956. Samples were collected weekly off Pt. Jefferson.

Source: Hebard, 1956.
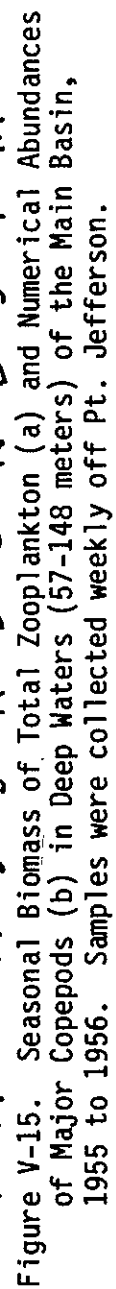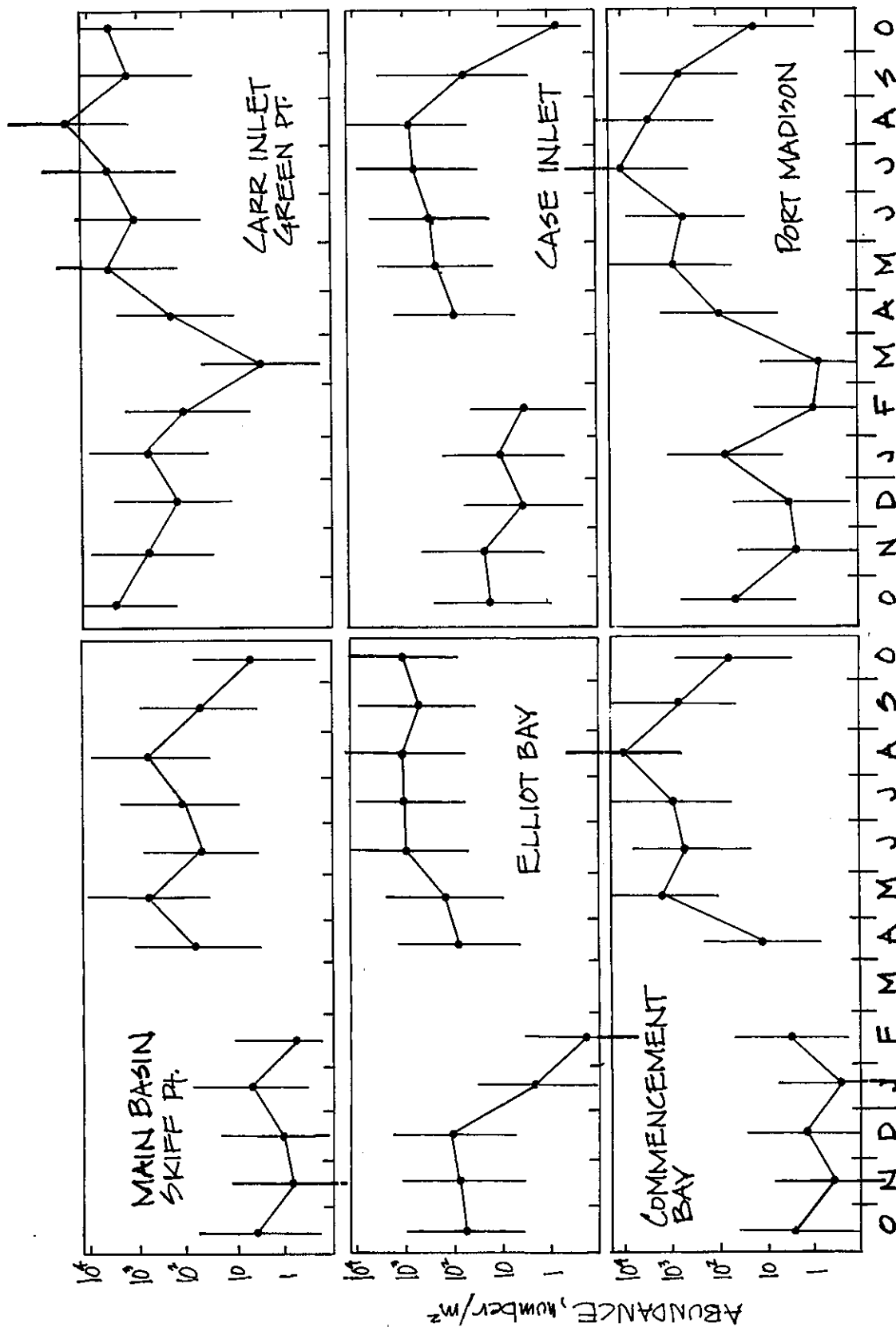
Figure V-16. Temporal Abundance of _Euphausia pacifica_ in the Main Basin and Selected Embayments. Samples were collected monthly, 1968 to 1969. Data are presented as mean abundances with 95 percent confidence intervals.

Source: Cooney, 1971.

Spatial Changes

Assessments of zooplankton abundance are complicated by its high degree of spatial heterogeneity. Ninety-five percent confidence limits of a single observation are typically 50 percent to 200 percent of the mean (King, 1979; Thorne, 1968; Cooney, 1971; Maynard, 1972). Although data are not available from Puget Sound, Mackas et al. (1980) found a highly negative spatial correlation between phytoplankton and zooplankton standing stocks in the Strait of Georgia. A principal source of "patchiness" in repeated observations is diel and seasonal vertical migration.

The reasons for vertical migrations are still unclear, but recent literature speculations, summarized by Enright (1979) and Wright et al. (in Kerfoot, 1980), center on predator avoidance. Cooney (1971) found some light avoidance in micronekton. Migratory ability is related to size; no migration has been documented in the microzooplankton, whose distribution in other Pacific waters is near the surface and correlated with concentrations of nanoflagellates (Shuman, 1978) and detritus (Alldredge, 1979). Among mesozooplankton, migration has been observed only in some of the larger genera, and only during the more mature life stages. Published information on diel migration of copepods in Puget Sound is provided only by Damkaer (1964) from Dabob Bay, Hood Canal, during winter, a season when, in the similar environment of Saanich Inlet, B.C., small non-migratory copepods are found at the surface and larger copepods are dormant in deep water, a situation atypical of the rest of the year (Koeller et al., 1979; see also Figure V-15). The only thorough, published information on seasonal and diel vertical migration in mesozooplankton from the Puget Sound area is that of King (1979) on Dabob Bay chaetognaths. Some seasonal data consistent with the above observations are provided from the Strait of Juan de Fuca by Chester et al. (1980), although these and the data of Hebard (1956) indicate that small copepods may be found at all depths. These studies suggest that many larger copepods and chaetognaths, near and during stages of sexual maturity, remain below 50-100 depth between October and March; during the summer they migrate between the surface at night and 50-100 m by day. Immature stages were found to remain near the surface.

Micronekton spatial distributions in Puget Sound have been studied more intensively using high-frequency acoustic scattering (Cooney, 1971; Thorne, 1968; Macaulay, 1978), consistently revealing discrete subsurface aggregations (Figure V-17). Some mesozooplankton were also found in association with this scattering layer. Finer-scale distributions were presented by Orr (1980). Because of this aggregation, spatial heterogeneity is greater in the vertical dimension than the horizontal.
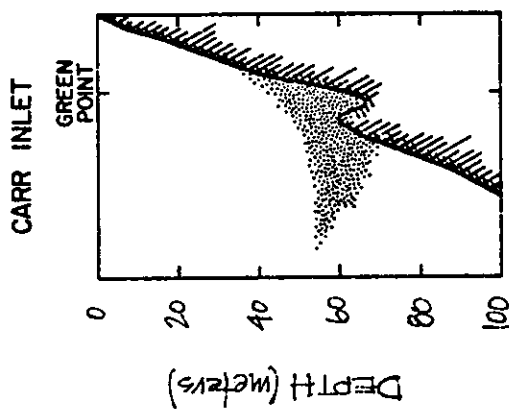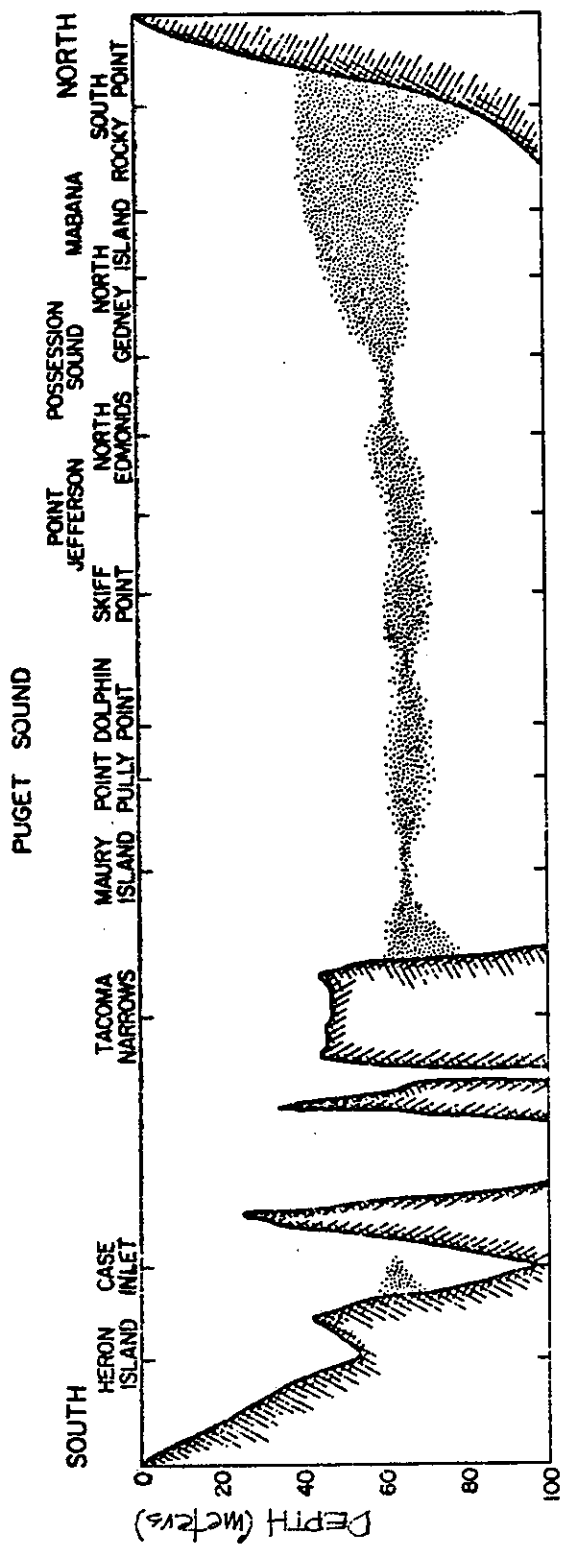
Figure V-17. Extent of 100 kHz Diffuse Sound Scattering Layers Observed in Puget Sound, July 1968.

Source: Cooney, 1971.

Diel vertical migration patterns of micronekton, visible in scattering data, extend deeper than those of mesozooplankton, indicating greater swimming ability of larger animals (Figure V-18). Seasonal depth of the micronekton scattering layer was found by Cooney (1971) to be complicated by the population life cycles and age structure. In the numerically dominant organisms, E. pacifica, the deepest living animals (75 m) were the adults which spawned near the bottom of Carr Inlet from May through July; most of the scattering was shallower (60 m) and caused by juveniles (larger than the 10 mm threshold of detectability) found in the Southern Sound all year and recruited into the main basin from April through September (Thorne, 1968; Hulsizer, 1972). The Whidbey basin may also serve as a source of recruitment to the Main Basin (Macaulay, 1978). Flushing and turbulence are believed to disrupt zooplankton aggregations at The Narrows all year (Cooney, 1971), and in the Main Basin during winter (English and Thorne, 1977; Hebard, 1956; Figure V-16).

The need for extensive vertical migration excludes some large zooplankters from areas of depth less than roughly 50 meters (Cooney, 1971; Thorne, 1968; Damkaer, 1964; Shuman, 1978), and excludes certain Calanus species from the Sound altogether (Fulton, 1973). No persistent differences in zooplankton standing stock can be found, however, among stations in the open Main Basin (Hebard, 1956; English and Thorne, 1977).

The observations cited above are graphically summarized in Figure V-19, which depicts how spatial and temporal distributions of Puget Sound zooplankton reflect possible life cycle strategies related to hydrography. Holoplankton animals must avoid being washed out to sea; microzooplankters and small copepods, and perhaps ctenophores and larvaceans, maintain their positions by means of short life cycles and high fecundity; larger copepods, chaetognaths and micronekton spend days below the depth of strongest outflow, and during the winter are most abundant deep in inlets subject to slower flushing and reduced turbulence. Mesoplanktonic larvae and cnidarians, in contrast, use seaward advection for dispersal, since the adult benthos and nekton escape washout. A benthic or nektonic species can, therefore, also better afford to restrict its spawning to specific times and places.

Embayments

Elliott Bay and Commencement Bay. Aron (1958) found copepods to be 85 to 92 percent of the zooplankton assemblage in Elliott Bay in January, comparable to the proportion found in the open Main Basin by Cooney (1971). Cooney (1971) also found the euphausiid population in Elliott Bay slightly higher than that in the open Main Basin, with the scattering layer persisting a month later in the season before dispersing in both embayments. The scanty data on Commencement Bay populations are comparable to those in the Main Basin (City of Tacoma, 1979).
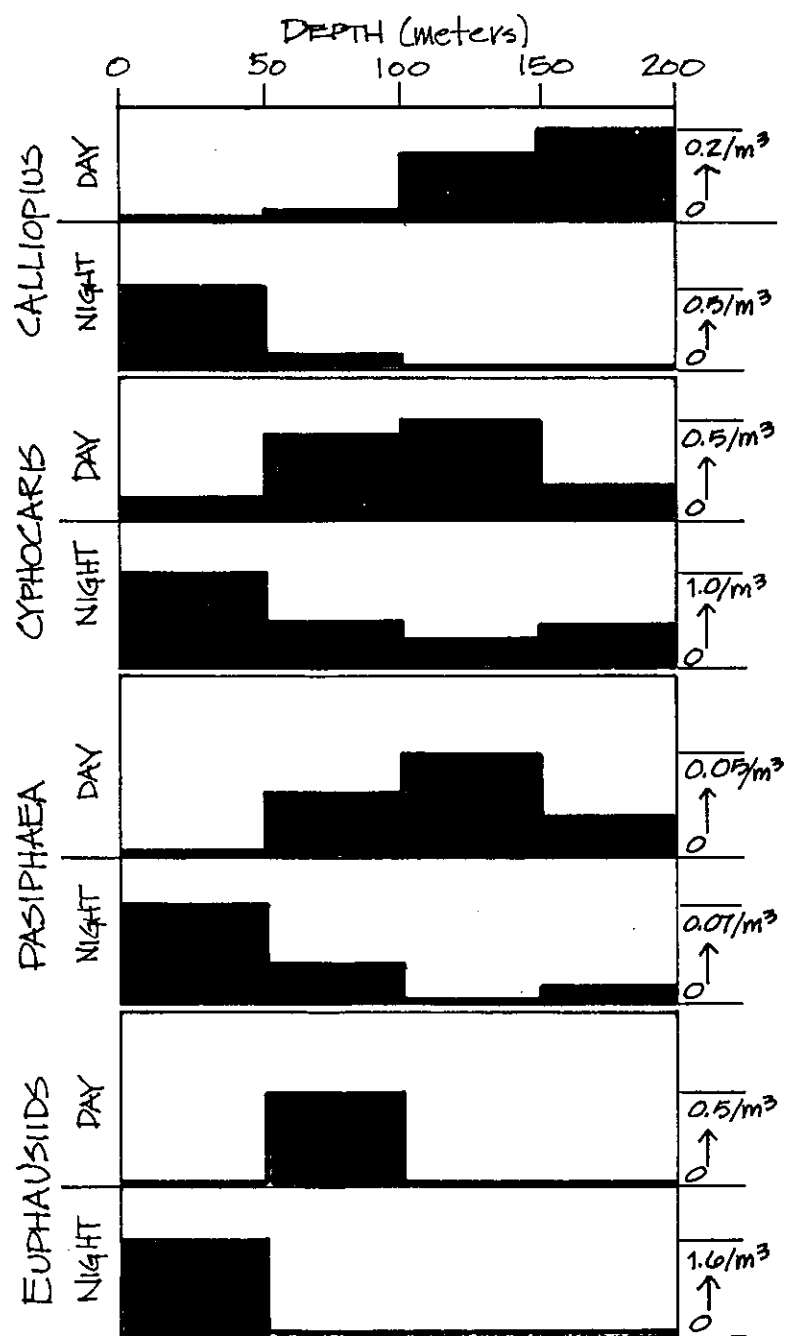
MAXIMUM CONCENTRATION, numbers/m³
(VARIES AMONG SAMPLES)

Figure V-18. Micronekton Diel Vertical Migration in the Main Basin, June 1968.

Source: Cooney, 1971.

-118-
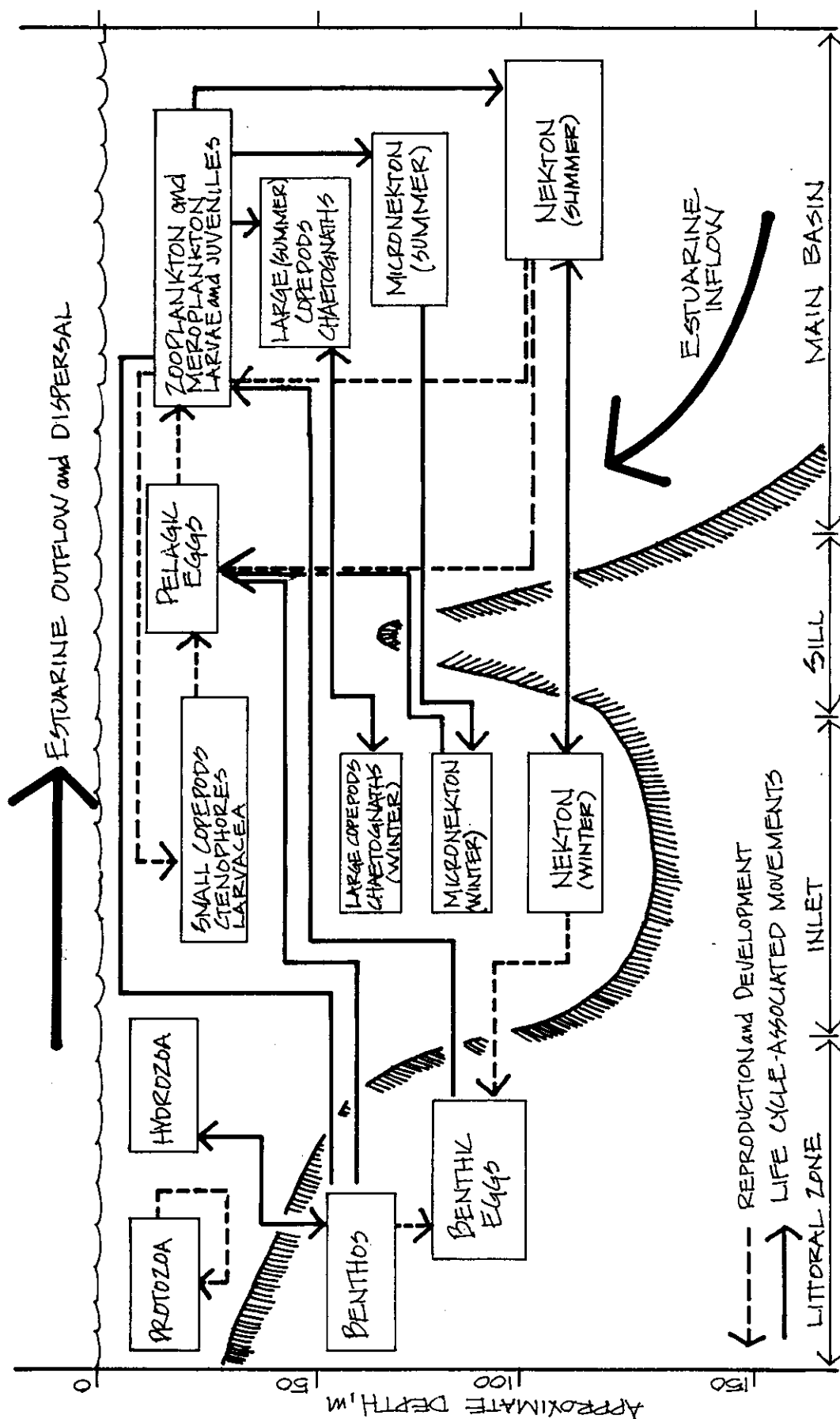
Figure V-19. Schematic Representation of the Dependence of Zooplankton Spatial and Temporal Distributions on Their Life Cycles.

-119-

Southern Sound. No zooplankton data are available from Budd Inlet.
Carr and Case Inlets serve as important nursery and overwintering
grounds for micronekton (Cooney, 1971). In one study, copepods (espe-
cially Calanus pacificus) were 60 to 80 percent of the biomass of
zooplankton in Carr Inlet; Euphausia, 3 to 33 percent; and Parathemisto,
4 percent (Cooney, 1971). Maynard (1972) found similar proportions,
with decapods and chaetognaths also significant. Euphausiids may be
more important in Carr Inlet (55 percent of copepod biomass; Cooney, 1971)
than in the Main Basin (4 percent). Increased food supply in spring and
warmer temperatures appear to enable euphausiid young-of-the-year to
spawn in Carr Inlet in the fall, an event not observed elsewhere
in Puget Sound (Hulsizer, 1972).

By contrast, mysids were more abundant than euphausiids in Case
Inlet (Thorne, 1968). The dominant mysid in the Main Basin, N. rayii,
was less numerous in Case Inlet than A. macropsis.

Calanoid copepods, followed by crustacean larvae, medusae, cteno-
phores, euphausiids, chaetognaths, and fish eggs and larvae dominated
zooplankton samples from the Nisqually Reach (Fresh and Cardwell, 1979;
Fresh et al., 1979). Little variation was seen with depth, unlike Carr
and Case Inlets, possibly due to the turbulent nature of the Reach.

Sinclair Inlet and Port Orchard. As in Case Inlet, mysids have
been reported to be the dominant micronekton group in Port Orchard.
Depths do not exceed 50 meters in this embayment; as a result, mysids
rest on the bottom during the day, constituting a significant fraction
of the crustacean epibenthos (Thorne, 1968). The commonest mysid in the
main basin, N. rayii, was less numerous here than N. kadiakensis. Cooney
(1967) observed the high-frequency zooplankton scattering layer in Port
Orchard and Sinclair Inlet to coincide with a lower-frequency scattering
layer of fish, including zooplanktivores such as herring, surf smelt,
midshipman, and tomcod. No studies of other zooplankton were identified.

NEKTON

Species Assemblage

This section deals with those free-swimming, pelagic species which,
as adults, can commonly be captured in open waters of Puget Sound away
from shore and bottom using tow nets, purse seines, or midwater trawls,
and which gain a major portion of their adult diet from pelagic prey, in
accordance with the definition of nekton (Sverdrup et al., 1942). There
is, however, overlap between the habitats of nekton in Puget Sound and
those of the nearshore and demersal fishes. The latter are dealt with
in Chapter 6.

A checklist of all Puget Sound fishes, with data on frequency of observation by area, is provided by DeLacy et al. (1972). Puget Sound nekton is divided, for purposes of this report, into three functional groups, based on size, life cycle, diet and habitat (Table V-4). Members of Group I, the salmonids, all belong to the same family, whereas the other groups are taxonomically mixed. Group II members are called baitfishes because, by virtue of their sizes, they are a principal trophic link between plankton and larger nekton in the pelagic food web. The two species of baitfish most frequently sampled in Puget Sound are herring and surf smelt. The Pacific sand lance is believed to be an important baitfish, but less is known about it due to sampling difficulties, and its abundance is probably underestimated. Group III, midwater nekton, is composed of larger, longer-lived species inhabiting deep water as adults, but not maintaining exclusive contact with the bottom. Shrimps or prawns are the only nektonic crustaceans in Washington waters. Species having the greatest commercial and sport value are also denoted in Table V-4. Illustrations of the vertebrate species may be found in Somerton and Murray (1976).

Life Cycles

Generalized life cycles for major nekton organisms are depicted in Figures V-20 to V-23. Further information on life cycles may be found in WDOE (1977) and Hart (1973), which are the sources for unattributed data below.

Salmonids are all anadromous, except for small landlocked populations beyond the scope of this report. The salmonid life cycle is depicted schematically in Figure V-20. Further information on salmon life cycles may be found in Williams et al. (1975), McNeil and Bailey (1975), and Verhoeven (1974). Life history details for cutthroat trout may be found in Johnston and Mercer (1976). Adults of all species lay eggs in gravel of rivers and streams during the fall and winter; salmon then die, but as many as a third of searun trouts may return to sea and spawn again the following year. After hatching, the young live on yolk in the gravel (alevin stage), emerge as fry during March and April and enter saltwater by June (in most species, after a year or more of freshwater feeding). After a variable stay in saltwater, spawning adults re-enter streams mostly in the fall. Each year's class of fish leaving and entering streams is a heterogeneous mixture of sizes and ages of different species. Fish return to their precise river of origin, thus each spawning ground supports a genetically distinct race, although this pattern is complicated by hatchery planting.

Figure V-21 shows a schematic baitfish life cycle. The principal species - herring, surf smelt, and sand lance - lay eggs in the intertidal and subtidal zones of sheltered inlets during the winter (although smelt may spawn year-round; Pentilla, 1978). Herring attach their adhesive egg clusters to eelgrass and other submerged objects, while smelt seek

TABLE V-4

NEKTON SPECIES OF MAJOR SIGNIFICANCE IN PUGET SOUND.

Species of major value as defined by WDOE (1977) are preceded by *.

Functional Group I: Salmonids (Family Salmonidae)

Salmon species
    * Oncorhynchus tshawytscha   King or chinook salmon
    * O. kisutch   Coho or silver salmon
    * O. nerka   Sockeye or red salmon
    * O. gorbuscha   Pink or humpback salmon
    * O. keta   Chum or dog salmon

Searun Trout species
    * Salmo gairdneri   Steelhead
      S. clarki   Cutthroat
      Salvelinus malma   Dolly Varden

Functional Group II: Baitfishes

Family Clupeidae
    * Clupea harengus pallasi   Pacific herring
      Sardinops sagax   Pacific sardine
      Alosa sapidissima   American shad

Family Engraulidae
      Engraulis mordax   Pacific anchovy

Family Osmeridae
      Hypomesus pretiosus   Surf smelt
      Spirinchus thaleichthys   Longfin smelt
      Thaleichthys pacificus   Eulachon (Columbia
                                   River smelt)

Family Ammodytidae
      Ammodytes hexapterus   Pacific sand lance

Functional Group III: Midwater Nekton

Family Pandalidae (Crustacea: Decapoda)
      Pandalus danae   Coonstripe or dock shrimp
      P. jordani   Ocean pink shrimp
      P. platyceros   Spot shrimp

TABLE V-4 (CONT'D)

NEKTON SPECIES OF MAJOR SIGNIFICANCE IN PUGET SOUND.

Species of major value as defined by WDOE (1977) are preceded by *.

Family Gadidae
   * Gadus macrocephalus   Pacific cod
     Microgadus proximus   Pacific tomcod
     Merluccius productus   Pacific hake
     Theragra chalcogrammus   Walleye pollock

Family Squalidae (Chondrichthyes)
     Squalus acanthias   Spiny dogfish

Family Chimaeridae
     Hydrolagus colliei   Ratfish

Family Anoplopomatidae
     Anoplopoma fimbria   Sablefish or blackcod

Family Batrachoididae
     Porichthys notatus   Toadfish or plainfin
                                 midshipman
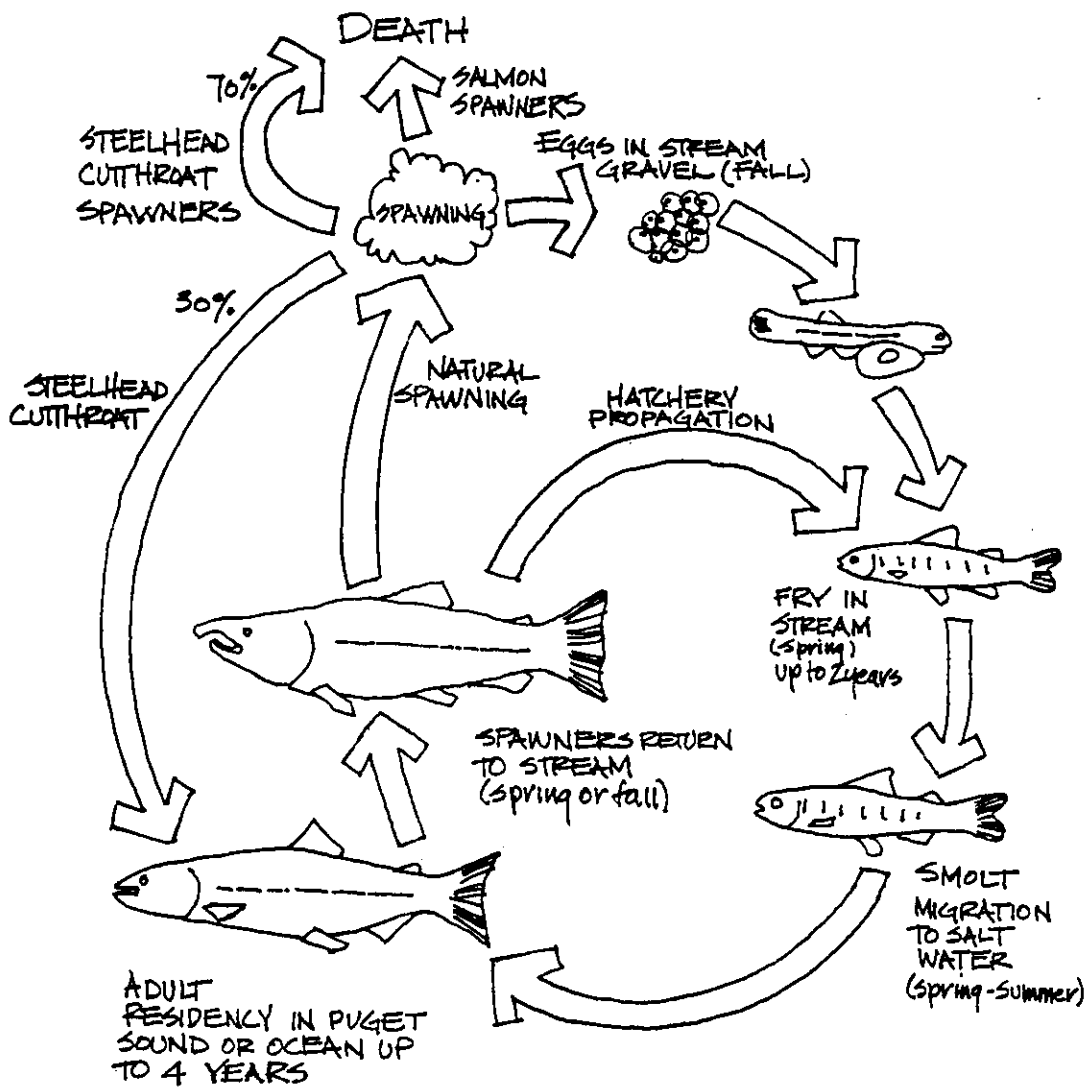
Figure V-20. Generalized Salmonid Life Cycle for Puget Sound.
Sources: McNeil and Bailey, 1975; Williams et al., 1975.
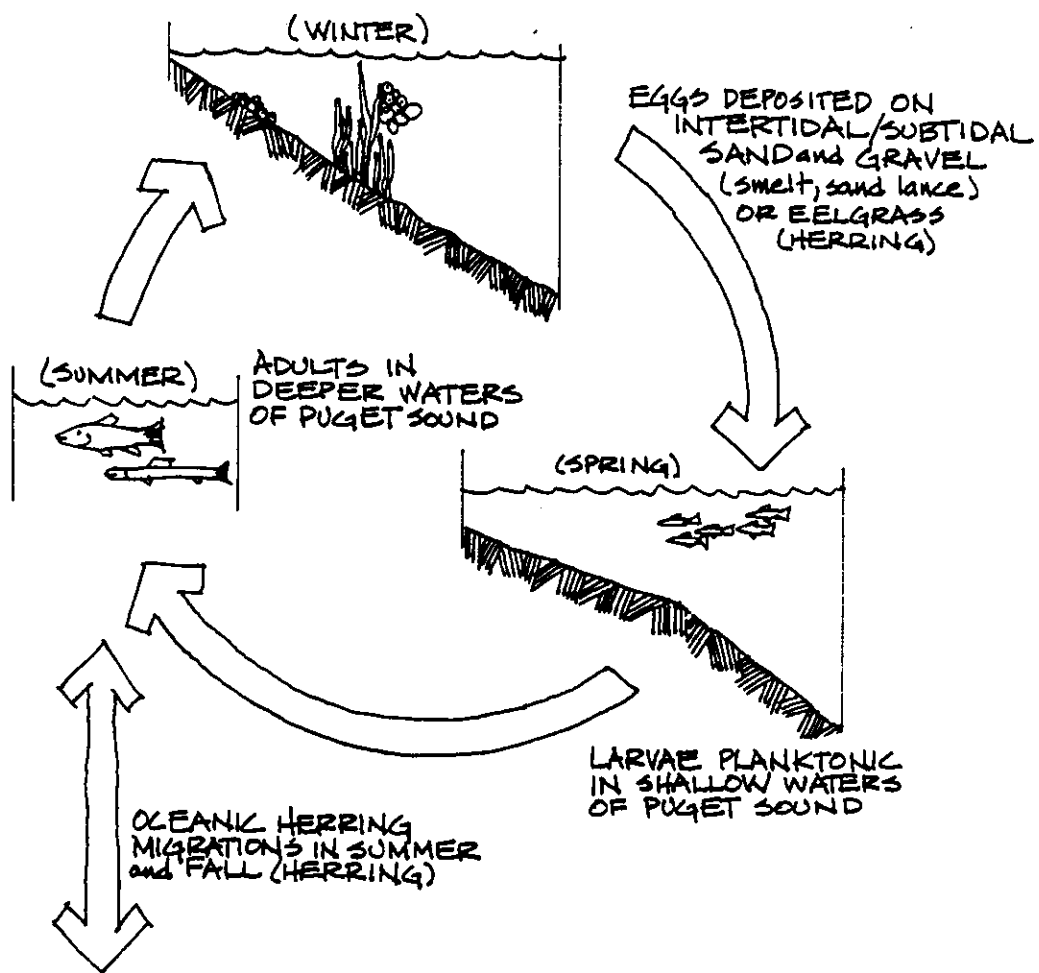
Figure V-21. Generalized Baitfish Life Cycle for Puget Sound.
Sources: Trumble, 1979; Pentilla, 1978; WDOE, 1977.
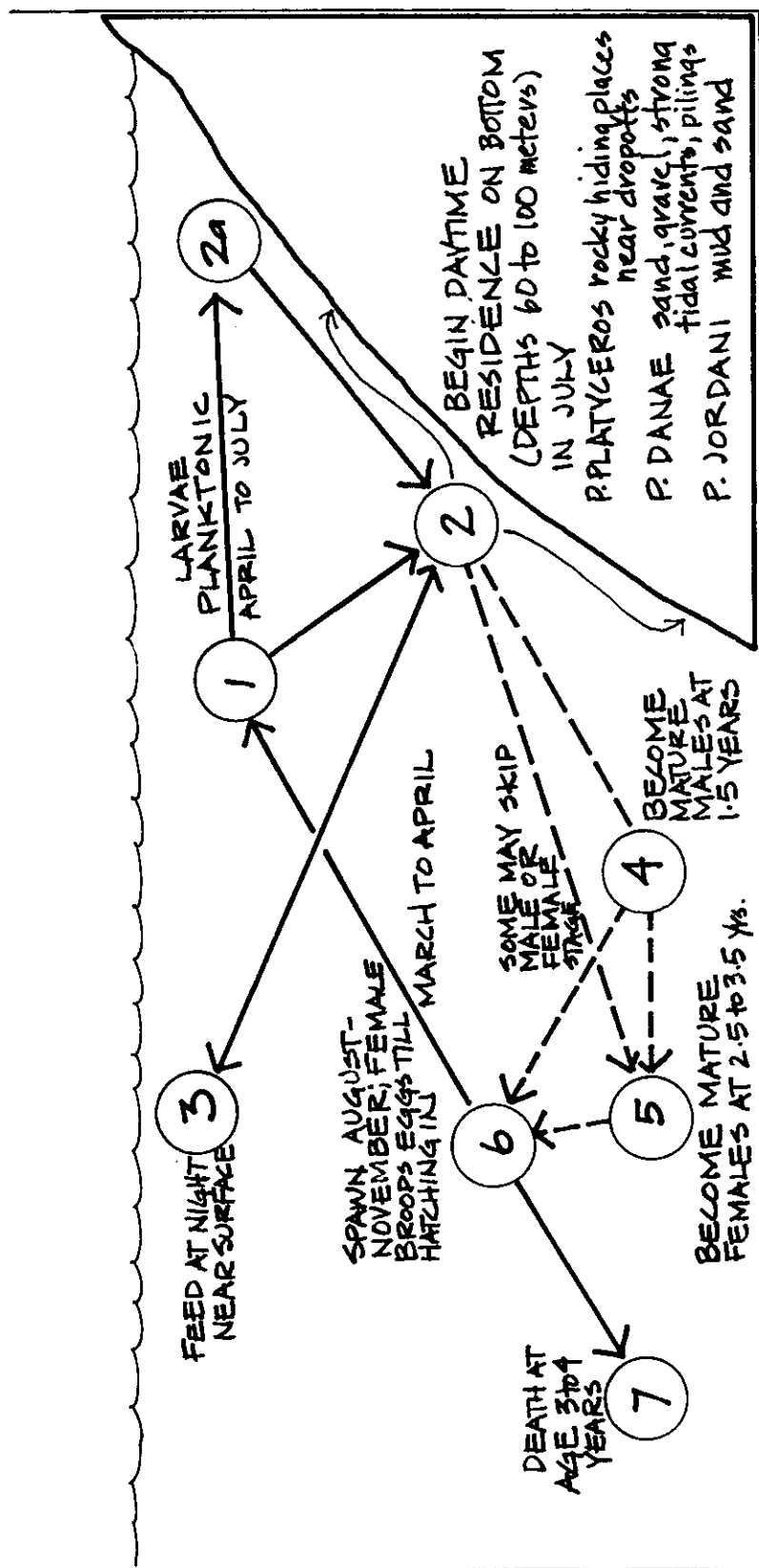
Figure V-22. Generalized Life Cycle for Pandalus Species of Shrimp in Puget Sound.

Sources: Magoon, 1974; Miller et al., 1974; Butler, 1980.
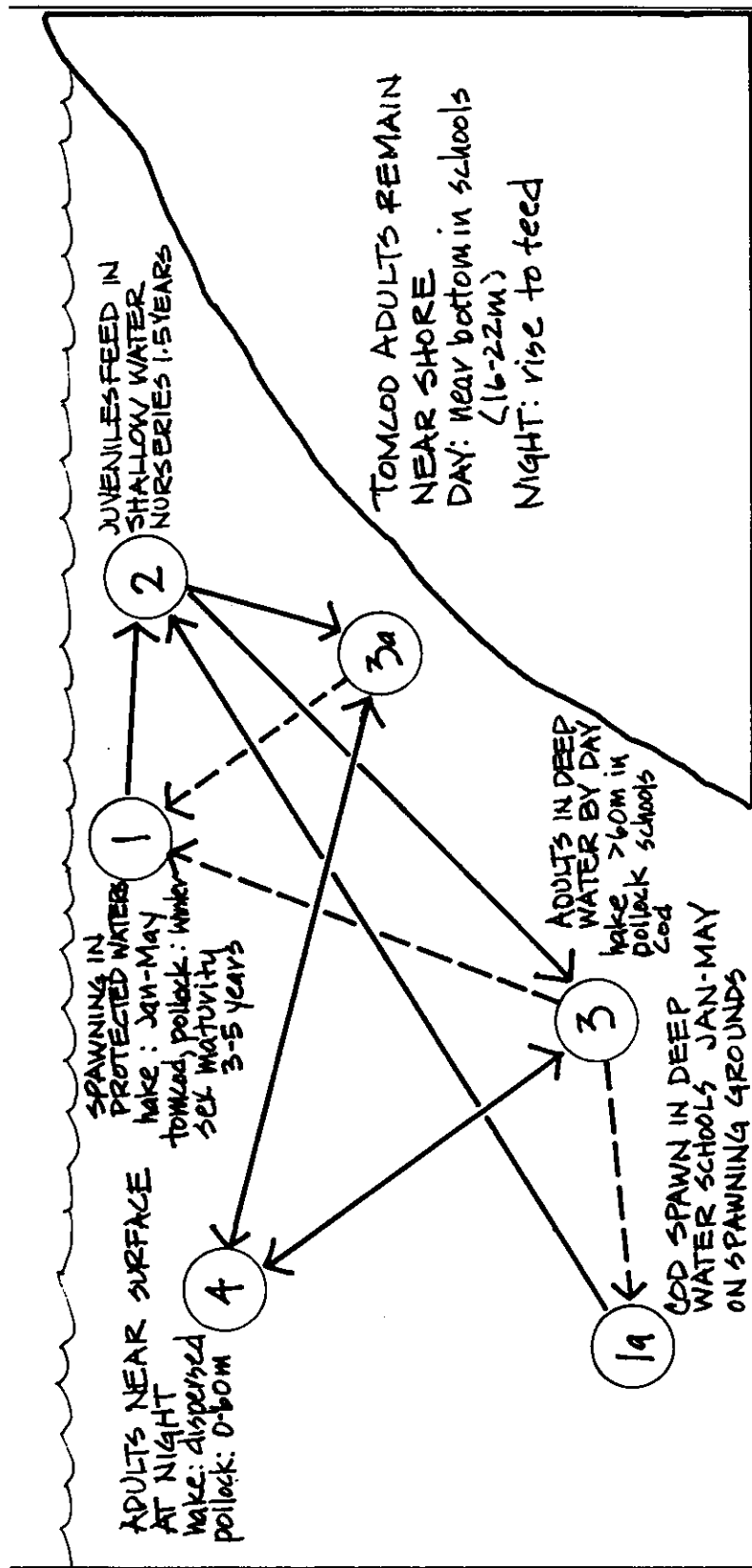
Figure V-23. Generalized Gadids Life Cycle for Puget Sound.

Sources: WDOE, 1977; Millikan, 1970; Galloway, 1977; Maynard, 1972;
Miller et al., 1978.

out beaches having the proper grain size, slope, and shading to ensure
that eggs remain moist without being swept away. Egg mortality due to
desiccation, injury, and predation by birds and juvenile fishes can
approach 90 percent for both species (Trumble, 1979; Pentilla, 1978).
Herring juveniles remain within the Sound for a year, then begin
a migratory pattern (see below). Herring may live up to eight years,
spawning each winter.

After hatching, surf smelt larvae are planktonic briefly. Surf
smelt spend the entire 3 to 5 years of their lives in the shallower
waters of Puget Sound, beginning to spawn at age 1 or 2 (WDOE, 1977).
Both herring and smelt form distinct races, each with a distinctive
beach of origin. The sand lance deposits its eggs subtidally on sandy
beaches during the winter. The young are believed to float in the
plankton until May and reach adulthood by September, living from 3 to 7
years (WDOE, 1977).

The longfin smelt and eulachon are anadromous, spawning in rivers
and lakes during the spring, but both are much less common in Puget
Sound than in more oceanic waters. Little is known of the marine
portions of their life cycles. The Lake Washington longfin population
is landlocked and does not enter Puget Sound (Moulton, 1970).

Life cycles of shrimps and gadids are portrayed in Figures V-22 and
V-23. Further details of Pandalus life cycles may be found in Butler
(1980) and Rothlisberg (1980). This group is unusual because most
individuals undergo both male and female life stages, possibly influenced
by fishing (Charnov, 1981). Life spans of gadids are from six years
(cod) to sixteen years (hake) with sexual maturity reached at 2 to 3
years (cod) and 3 to 5 years (hake) (WDOE, 1977). The spiny dogfish is
ovoviviparous, brooding its young during their 13-month gestation (Jones
and Geen, 1976 and 1977) and is pelagic for all of its 20 to 30 year
life span (Beamish and Smith, 1976). The ratfish spawns all year,
mainly in late summer and early fall. Its eggs incubate in the intertidal
zone. The toadfish or plainfin midshipman spawns in the spring and
summer, laying eggs in nests in the intertidal zone, and its larvae are
pelagic. The sablefish or blackcod, a commercial bottomfish on the open
coast, spawns in open water during January and February, and the young
rear in shallow water. It reaches sexual maturity at 4-to-5 years and
lives 20 years or more. According to Washington (1977), only immature
sablefish are found in Puget Sound.

Spatial/Temporal Distributions

Salmon populations in Puget Sound may be divided into three
components: out-migrating feeding juveniles, resident adults, and
in-migrating adults. Juveniles spend one to four months after entering
saltwater feeding progressively farther from shore (Fresh et al.,
1979). Between July and September most of these fish enter the open

Pacific and may migrate as far as the Aleutians. When they re-enter the Sound before spawning they feed little. Some of the juveniles, particularly those retained longer in hatcheries and net-pens (Haw and Bergman, 1972), never enter the Pacific and become resident adults, which form the basis of the Puget Sound sport fishery. The generalized migratory cycle of salmon is shown in Figure V-24.

Salmon are a major component of the Puget Sound pelagic assemblage only as juveniles; neither residents nor in-migrators form a major fraction of the fishes captured in midwater trawls (Maynard, 1972; Wingert and Miller, 1979). Accordingly, the most important habitats for salmon in Puget Sound are believed to be the nearshore and estuarine zones, in which early feeding and the physiological transition to saltwater take place. Parker (1968) estimated that the marine mortality of British Columbia salmon was highest during the first 40 days in saltwater. Estuaries would be especially critical for pinks and chums, which begin their feeding there. Gallagher (1979) has reviewed the influence of early marine conditions on pink and chum survival, and Wetherall (1971) provided further estimates of mortality rates for chinooks. For all salmon species, however, mortality is highest during larval freshwater residence. Mathews and Olson (1980) and Williams et al. (1975) have discussed causes and magnitudes of freshwater salmon mortality.

Due to the predominance of the nearshore juvenile stage, the distribution of salmon in Puget Sound is closely related to the location and capacity of spawning streams. Figure V-25 presents estimates of the run sizes of each salmon species to the major watersheds in the study area. These returns are dictated in part by the preferences of each species for spawning habitat. Sockeye, because they require lakes for rearing, are found only in the Lake Washington system. Pinks, preferring glacial streams, are most abundant in the Puyallup and Nisqually. Chinooks, the largest of the salmon, also prefer the largest and longest rivers, particularly the Duwamish and those in the Lake Washington drainage. Chums are found in small, flat, lowland valley streams such as abound in the Shelton and East Kitsap watersheds. Coho use both small and large streams for spawning, and so are the most widely distributed species. Figure V-25 also shows areas of Puget Sound utilized for sport fishing of salmonids, including steelhead and cutthroat, and for commercial salmon fishing (WDNR, 1977). Additional sport catch data are provided by Hoines et al. (1978).

The considerable variability of life cycles between different salmon species is depicted in Figure V-26 (Williams et al., 1975). Variations which exist between races within each species are not shown. Pink salmon live only two years, and enter saltwater directly after
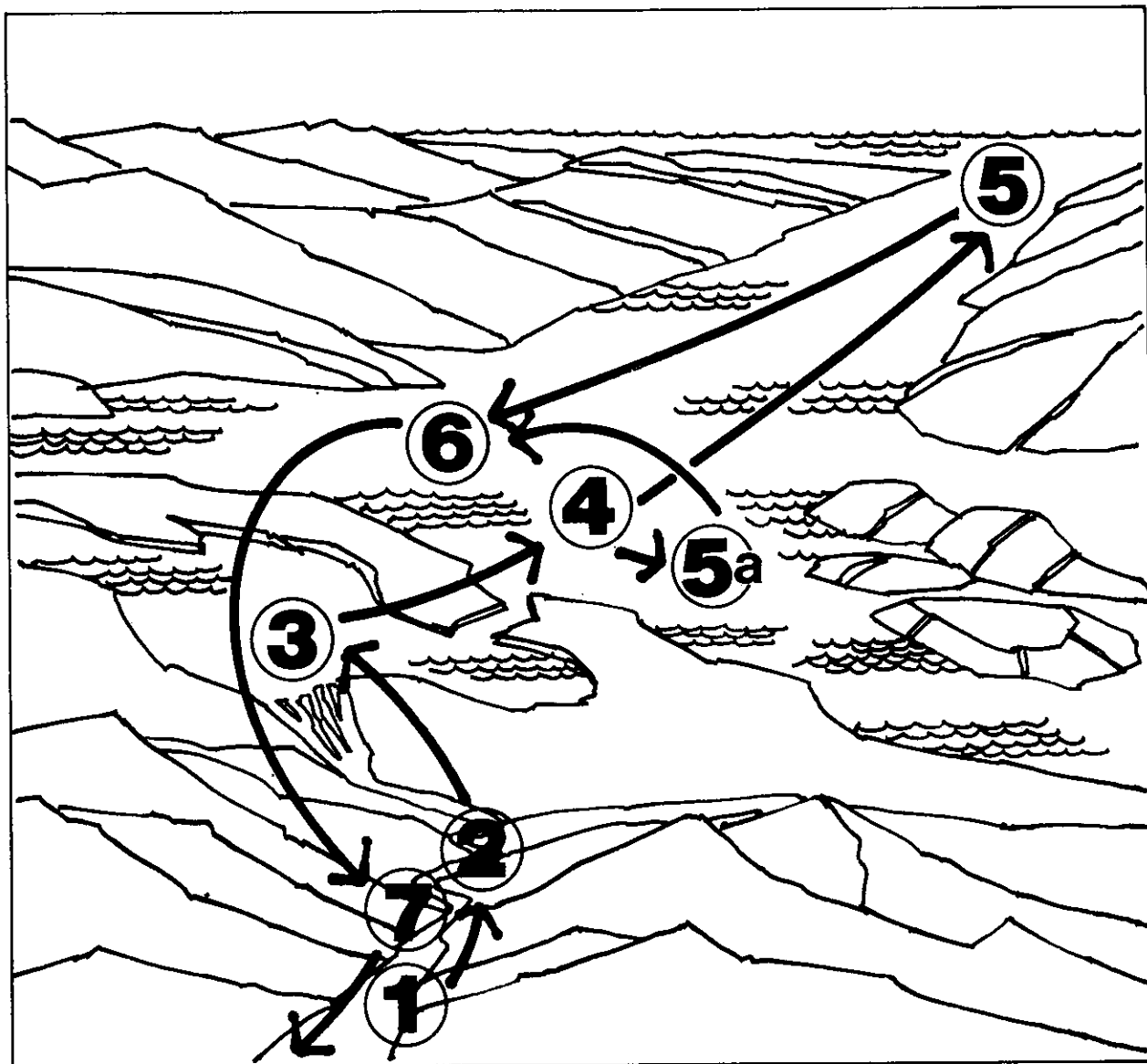
① EGGS: November to February

② FRESH WATER FRY: hours to 2 years (pink, chum, and fall chinook) (coho, sockeye steelhead, cutthroat, and spring chinook)

③ NEARSHORE EPIBENTHIVOROUS JUVENILES: March to June

④ OPEN SOUND PLANKTIVOROUS and PISCIVOROUS JUVENILES MAY to August

⑤ₐ RESIDENT ADULT CHINOOK and COHO

⑤ OPEN PACIFIC OCEAN arrive July and later remain 1.5 to 4 years

⑥ NONFEEDING ADULT INMIGRANTS return February to November Age: 2-5 years

⑦ SPAWNED ADULT SALMON DIE SOME CUTTHROAT AND STEELHEAD RETURN TO SEA

Figure V-24. Generalized Salmonid Migratory Cycle for Puget Sound.

Sources: Williams et al., 1975; Verhoeven, 1974.
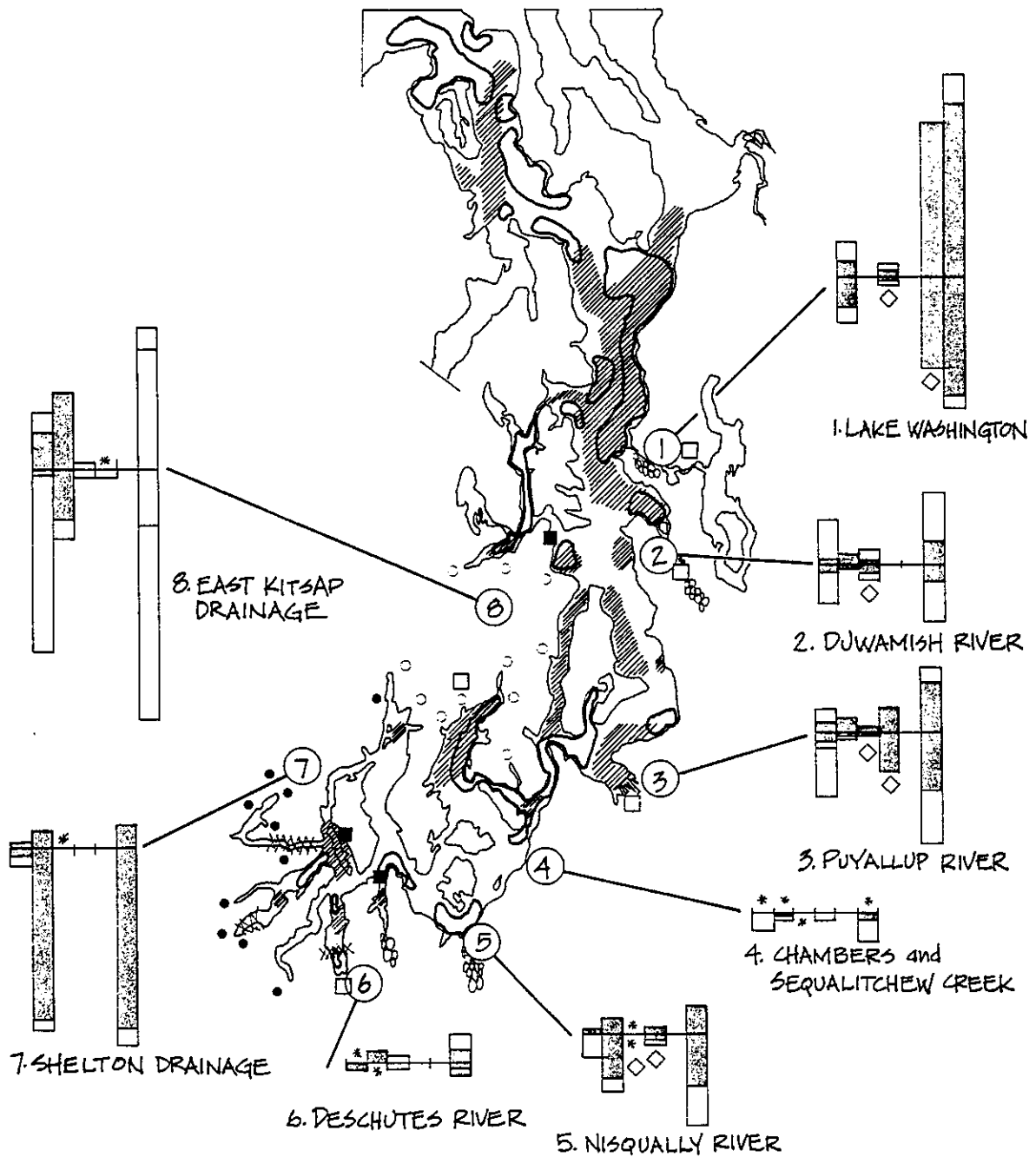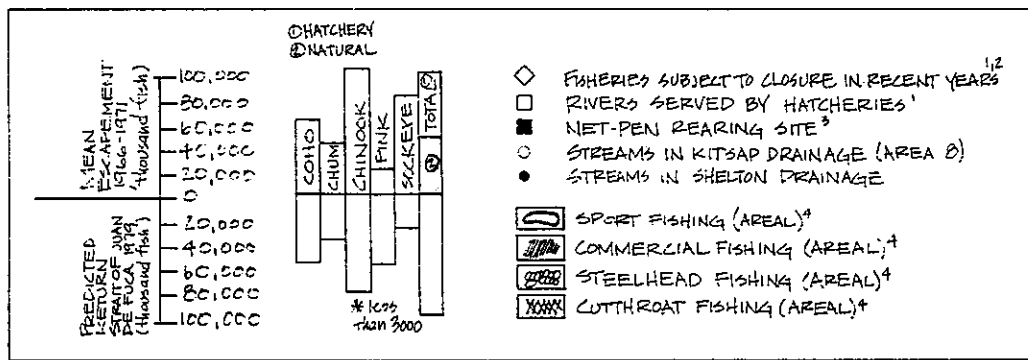
Figure V-25.   Salmonid Abundance Map for the Main Basin and Southern Sound Drainage Basins. Data From: 1. Williams et al., 1975 2. Harvest Management Division, 1979 a,b,c, and d. 3. Moring, 1973; Pease, 1977. 4. WDNR, 1977
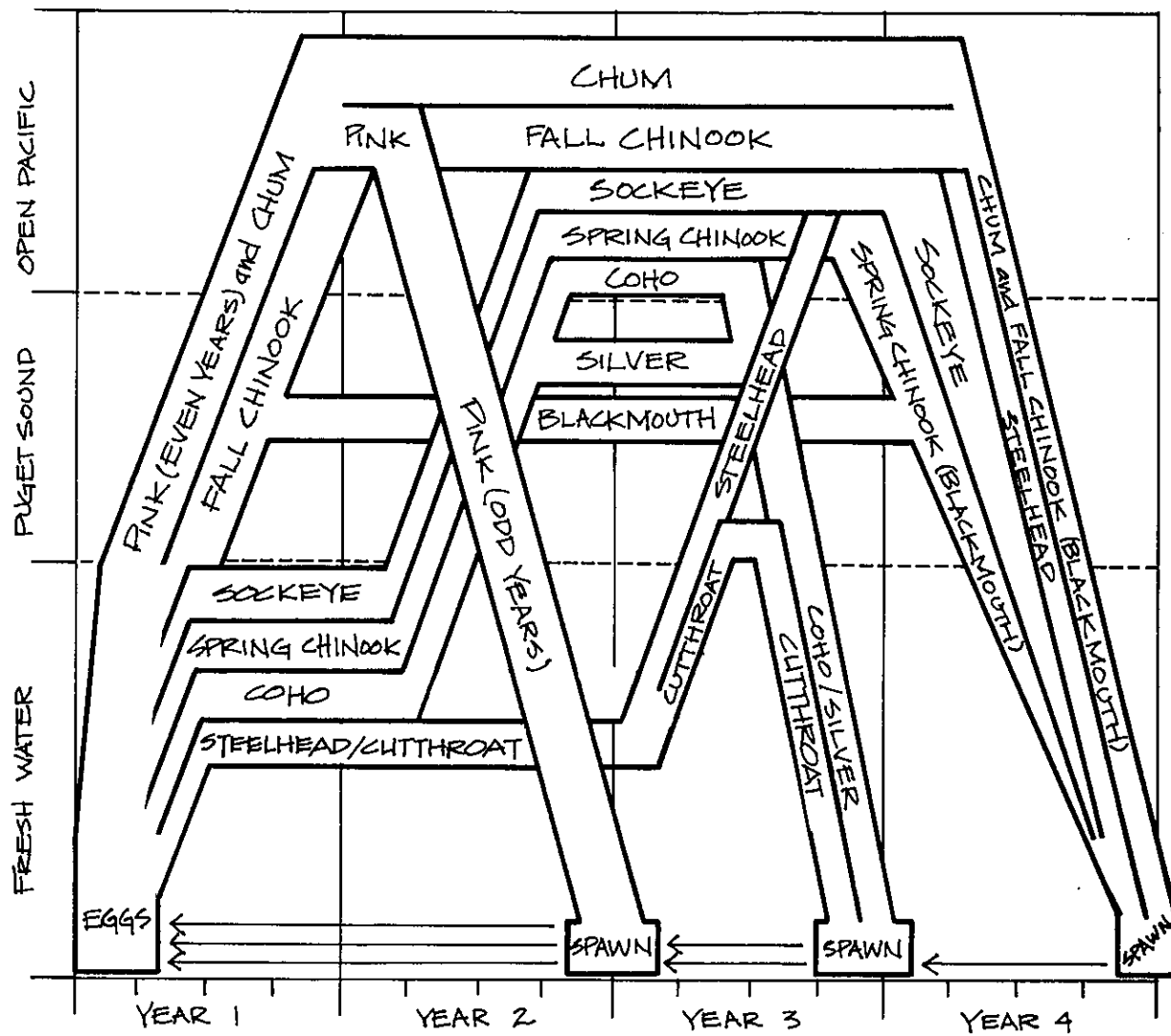
Figure V-26. Temporal Occurrence of Salmon in Puget Sound and Contiguous Waters.

Source: Williams et al., 1975.

emerging as fry between March and May, with no freshwater feeding stage. In Puget Sound, furthermore, only the race which spawns in odd-numbered years (i.e., 1979, 1981) and produces young in even-numbered years is present; the complementary race has never been observed. Chum salmon also enter saltwater directly, but live four years or longer. Both linger in shallow estuary zones 1 to 2 months before beginning oceanward migrations.

Two races of chinook are found in Puget Sound: the more abundant fall race enters freshwater, usually aged four years, between August and October, while spring chinook enter earlier from February to May, in order to reach spawning grounds further inland. Juvenile fall chinook feed briefly in freshwater before following the juvenile pink and chum salmon into Puget Sound between May and July. Juvenile spring chinook spend a year or more feeding in rivers. Coho juveniles also spend a year in freshwater (except for populations in small streams which do not carry enough water to support fish in midsummer), and usually finish their life cycle at age three. Resident populations of fall and spring chinook (called blackmouths) and of coho (silvers) follow the same patterns as their seagoing relatives, and are believed to originate mostly from the more southerly streams (Allen, 1956). A former population of resident pinks is virtually extinct. Sockeye, which require lakes for rearing of juveniles, spend a year or more in freshwater, and return from the sea beginning as early as May at 4 to 5 years of age.

Searun trouts follow a similar pattern. Returning adult steelhead form summer (May-October) and more abundant winter (November-April) races. Fry emerge in April and May and spend 1 to 2 years in fresh water, and an additional two years at sea (DesVoigne et al., 1975; WDOE, 1977). Cutthroat, in contrast, never stray far from their rivers of origin, spending the summer feeding nearshore beginning at 2 to 4 years of age, and spawning during the fall and winter with a peak in November (WDOE, 1977; Johnston and Mercer, 1976).

Many Puget Sound salmon populations have declined seriously from aboriginal population levels (Buckley, 1969; Haw and Bergman, 1972). The harvest of coho, the most abundant species in the Main Basin and Southern Sound, is sustained only by hatchery propagation (Mathews and Olson, 1980), and the stocks of resident silvers are estimated at 25 percent of their former levels. The spring chinook race is nearly gone (Barker, 1979). Salmon stocks which are depleted and subject to fishery closures are noted in Figure V-25, along with the locations of hatcheries. Steelhead, chinook and coho, plus a few pinks and chums, are raised in hatcheries. Some hatchery fry are planted in streams which are not served by their own hatchery; data are presented by Fletcher (1979) and Dunn et al. (1979).

Artificial propagation increases the juvenile population in four ways: by reducing the estimated 90 percent mortality of eggs, by supplementing feeding of fry and thus effectively expanding the rearing habitat, by controlling the timing of juvenile release to coincide with optimal conditions, and by permitting selective breeding. Hatchery rearing also permits almost an entire run of spawners to be harvested, with near-zero natural escapement, since the eggs of only a few individuals are required for propagation, but this has the side-effect of reducing genetic diversity. It is suspected that resident stocks may have declined in part because previous hatchery propagation practices seemed to select against them (Buckley, 1969; Haw and Bergman, 1972). This effect may be partially offset by proper timing of juvenile release.

The potential for hatchery enhancement is further limited by the carrying capacity of marine waters; increasing the release of juveniles is fruitless if there is not natural food to support them once freed, or if predators remove them all (e.g., Bailey et al., 1975). Gallagher (1979) noted the borderline adequacy of food for young pinks and chums in Puget Sound, and Kaczynski et al. (1973) noted that large reductions in stocks of pinks have occurred despite the coincident tripling of hatchery outputs. Efforts now are under way to raise juveniles in captivity in saltwater net-pens to further control feeding and mortality, at locations marked in Figure V-25 (McNeil and Bailey, 1975; Moring, 1973; Pease, 1977; Rensel, 1976).

Figure V-27 shows the observed distribution of herring and surf smelt eggs along Puget Sound beaches (Trumble et al., 1977; Pentilla, 1978). Similar data are presented by Koons and Cardwell (1981). The Southern Sound includes half of the known surf smelt spawning grounds on the Sound, while most herring roe has been found in the Northern Sound and the Strait of Georgia. Populations spawned in the Northern Sound are not believed to use the Southern Sound as a nursery. A nearshore baitfish community sampled by beach seine in the Main Basin was dominated by sand lances over eelgrass substrates, such as at Alki Point and Point Pully, while tomcod was the dominant nearshore fish over sand at West Point (Wingert and Miller, 1979). Eelgrass sites also had higher fish biomass and species diversity.

Figure V-28 shows the hypothesized migratory cycle of the herring (Trumble, 1979). Beginning when herring reach bait-size (4") during the fall of their first year, they are acoustically observed in tight schools at depths greater than 40 meters during the daytime, dispersing and rising to 10 to 30 meters at night to feed. For those herring occurring within the study area, the Southern Sound is vital for sheltering juveniles, resident adults, and migratory adults just before spawning.
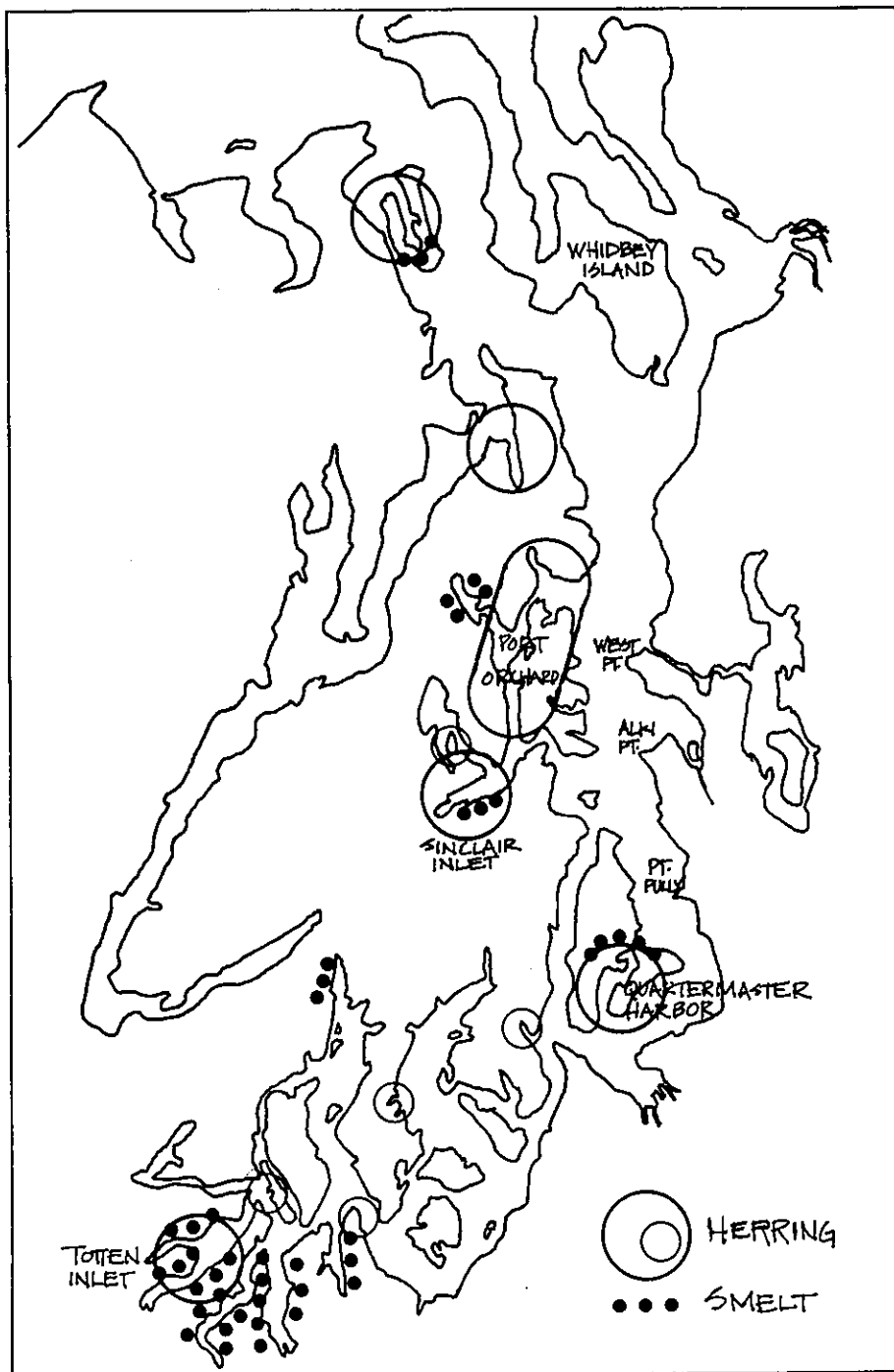
Figure V-27. Herring and Surf Smelt Spawning Beaches in Puget Sound.

Sources: Herring -- Trumble et al., 1977, Smelt -- Pentilla, 1978; Also
WDNR, 1977; WDOE, 1977 through 1980.
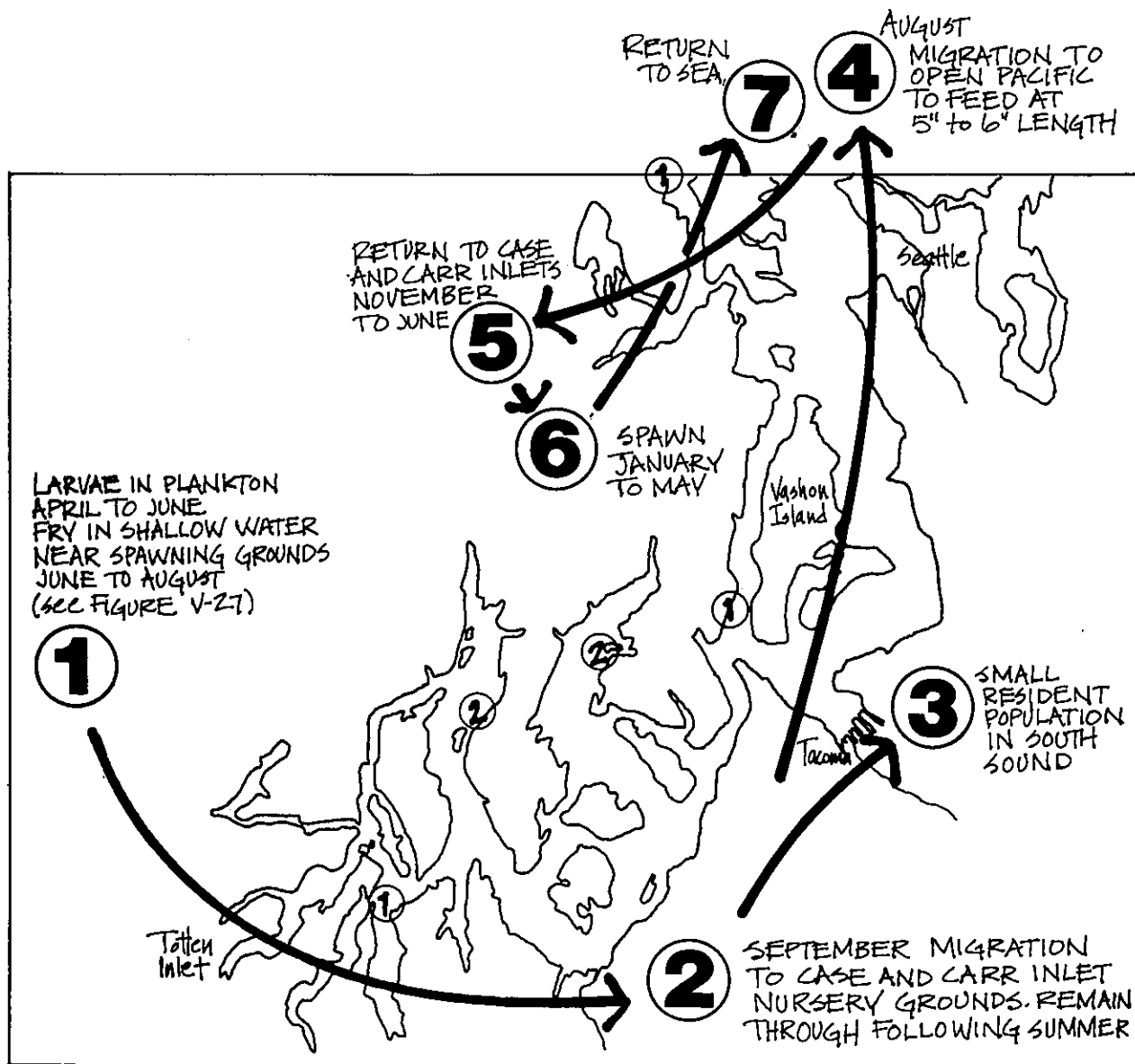
Figure V-28. Probable Migratory Cycle of Southern Puget Sound Herring
Populations.

Source: Trumble, 1979.

At the time of peak biomass in November and December, up to 6 million kilograms of adult and 7 million kilograms of juvenile herring have been estimated to reside in the Southern Sound, especially in Case and Carr Inlets (Lemberg, 1978), and herring may comprise more than 80 percent of the biomass of all pelagic fishes in the Southern Sound (Maynard, 1972). Fewer herring are observed in the Main Basin, which is believed to be primarily a migratory zone. Their schooling habits and migratory behavior, however, make precise estimates of herring biomass difficult. Juveniles are observed in shallower water than are adults. A significant decline in herring biomass in the Southern Sound, from the 1975 levels above to only 2 million and 3.5 million kilograms of adults and juveniles, respectively, in 1978, is thought to have resulted simply from migratory reactions to drought and flooding; it cannot be linked to overfishing, nor to the commercial harvest of roe in the Northern Sound (Trumble, 1979). The population recovered to some extent in the winter of 1979-1980 (O'Connor, 1980). Earlier data on herring harvest are provided by WDOF (1978).

Few estimates are available on the abundance of other baitfishes. Fresh et al. (1979) found sand lance second only to herring in townet abundance off the Nisqually Delta, where it rears as a juvenile. Sand lances are believed to burrow into the sand by day, and feed in schools off the shallow bottom by night. Their abundance is thought to have declined in recent years due to bait harvest (WDOE, 1977). Sardines and anchovies, more common on the open coast and in warmer water, are much less abundant than herring in the Main Basin and Southern Sound, but their migration patterns are similar to those of herring, and their maximum populations are found in the Southern Sound inlets (WDOE, 1977). Their appearances, like those of the herring, are sporadic (Maynard, 1972). The shad is seldom found in the Southern Sound, although the Nisqually River would seem an ideal habitat for its anadromous life cycle.

Shrimp fishing areas in Puget Sound have been mapped by WDNR (1977). All three of the major Pandalus species in Puget Sound, as well as four others, are found in commercial quantities along the Pacific Coast from California to Alaska, but yield a much smaller harvest than the penaeid shrimp of tropical seas, including the Gulf of Mexico (Butler, 1980). Pandalus platyceros have been observed to be most abundant in Elliott Bay, P. danae in Port Orchard, Eagle Harbor and the mouth of Budd Inlet, while P. jordani were found mainly in Carr Inlet (Magoon, 1974). More recent data (Malins et al., 1980) indicate signi- ficant abundances of P. jordani in Main Basin areas, including Elliott Bay. Comparison of studies (Magoon, 1974; Malins et al., 1980), suggest considerable spatial and temporal variability. P. danae also frequents an artificial reef off Edmonds (Hueckel, 1980). Catches of these species have declined significantly in recent years; commercial shrimping

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has been outlawed in Elliott Bay since 1971 and in Carr Inlet (where landings just began in 1973) since 1978. Most commercial catches in Washington come from elsewhere in the Sound and Hood Canal, and from the open coast. Some catch data are provided by Magoon (1974) and WDOE (1977), showing that the Elliott Bay catch dropped from over 20,000 pounds in 1958 to barely 200 pounds in 1971. Experiments on ranching of young shrimp in Puget Sound have been conducted in Henderson Inlet and Port Orchard (Rensel, 1976; Rensel and Prentice, 1978 and 1980).

Areas for sport fishing of gadids and other sandy substrate deep water fishes are shown in Figure V-29. More detailed maps of distribution by species are provided by Washington (1977) and Miller and Borton (1980). All species of midwater fishes are ubiquitous in the study area, although inshore stocks migrate little and are genetically distinct from coastal populations (Galloway, 1977; Ketchen, 1961). Cod and hake are more abundant in the Northern Sound than in the study area. The Main Basin provides less than 3 percent of the commercial cod catch from Washington inland waters (Gosho, 1976), and commercial quantities of hake are not found south of the Whidbey Basin (Millikan, 1970; Kimura and Millikan, 1977; Galloway, 1977). According to WDOF (1978), however, the Central and Southern Sound account for 75 percent of the state's recreational groundfish catch, half of which is composed of gadids. Supporting data are provided by Hoines et al. (1978). Tomcod are equally abundant in all areas of the Sound, while pollock are most abundant within the study area (WDOE, 1977). The smaller (30 cm versus 1 m for other gadids) tomcod is found shallower and closer to shore than other members of the cod family (Wingert and Miller, 1979). The most common midwater fish off Alki Point, Point Pulley and West Point in that study was the ratfish (Miller et al., 1977a and 1977b).

Midwater trawls in the Main Basin have captured fewer fishes than trawls in embayments and other more sheltered waters; this difference is confirmed by acoustical assessments (Thorne, 1970; English and Thorne, 1977). Abundances were lowest in February, and dominated by juvenile dogfish and juvenile and adult herring and hake. Peak abundance was in September, largely due to an influx of out-migrating juvenile herring from the Southern Sound; hake and pollock were also consistently present. Little consistent horizontal structure was found in abundances within the Main Basin, most likely due to vigorous mixing. Shilshole Bay is listed by WDOE (1977-1980) as a critical habitat for longnose skate.

The dogfish in the Southern Sound is found at depths of 60 to 90 m during the day, and feeding at 0 to 30 m at night (Maynard, 1972). It schools by age and by sex, but does not migrate extensively. Dogfishes were fished commercially in the Southern Sound for a brief period during
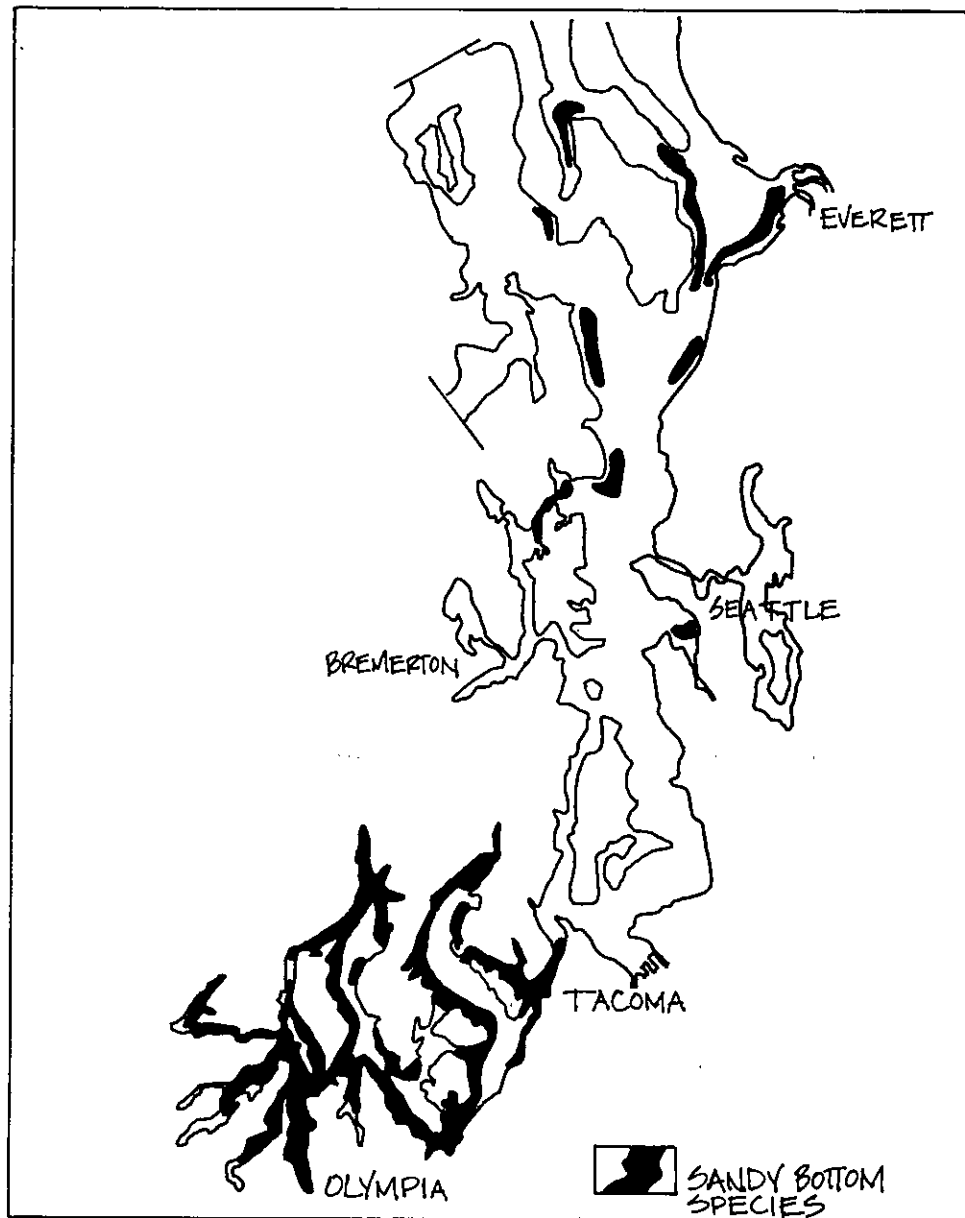
Figure V-29.   Areas in Puget Sound for Sport Fishing of Sandy Bottom Fishes
    Including Gadus sp., Anoplopoma sp., Squalus sp., and Theragra sp.

Source: WDNR, 1977.

the 1940s for the vitamin A in their livers, but the fishery began declining even before the vitamin was synthesized artificially, probably due to a failure of recruitment from the Main Basin. The present population of the Southern Sound is estimated at around 1 million fish and 2 million pounds. A fishery was revived in 1975, but the Southern Sound and Main Basin provide, at most, about 10 percent of the total inland catch (Fujioka, 1978). The catch must be exported because of high mercury content (WDOF, 1978).

The ratfish is poorly studied, but appears to be ubiquitous in deep water, at depths from 50 to 100 m, throughout the Sound (DeLacy et al., 1972; WDOE, 1977; Wingert and Miller, 1979; Miller et al., 1977a and 1977b). While frequently found in midwater trawls, the ratfish is the most bottom-oriented of the midwater community, having a primarily benthic diet (Wingert et al., 1979). Quinn et al. (1980) observed a nocturnal migration of smaller individuals into shallower water.

Blackcod, both juvenile and adult, rest on or in the bottom at depths of 100 meters or more during the day, and migrate upward at night to feed. They are less common in the Southern Sound than in the Main Basin (DeLacy et al., 1972).

Embayments

Elliott Bay. Elliott Bay is a migratory route and a juvenile nursery area for the salmonid species (fall chinook, coho, chum, steelhead, cutthroat, and Dolly Varden), which utilize the Duwamish waterway. In addition, sockeye, chinook, and coho (and steelhead, cutthroat and Dolly Varden) use the Lake Washington drainage just to the north. The area supports heavy sport fishing and some commercial fishing (Figure V-25).

Pollock, hake, tomcod, cod, ratfish, dogfish, and salmonids, in addition to rockfishes, perches, sculpins and flatfishes, were taken by gill net off the developed waterfront of Elliott Bay (Port of Seattle, 1976a and 1976b). In the southeast Bay, 37 chinook and coho juveniles, together with anchovies, composed the majority of the summer catch in surface nets. Chum have been scarce in recent years, possibly due to predation by coho. Bottom hauls were dominated by adult pollock and hake in the winter, but by perches in the summer; soles and rockfishes were uncommon. (The methods used would not have captured juvenile herring, or other similarly sized baitfishes). Elliott Bay is also prime habitat for the spot shrimp, Pandalus platyceros (Magoon, 1974).

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In beach seine hauls from the Duwamish Waterway, the most common species were chinook, coho and chum (seasonally), along with herring, surf smelt, shiner perch, staghorn sculpin, and threespine stickleback. Less common were cutthroat, steelhead, Dolly Varden, tomcod, sand lance, pollock, longfin smelt, and lamprey (Matsuda et al., 1968). Otter trawls in the Duwamish Waterway most commonly caught herring, longfin smelt, and tomcod when salmon were not present. Longfin were seasonal, reaching maximum abundance during late summer and fall (Miller et al., 1977a and 1977b).

Commencement Bay. Commencement Bay is a migratory route and a juvenile nursery area for the salmonid species which utilize the Puyallup waterway - spring and fall chinook, coho, pink, and chum, steelhead and cutthroat. Small populations of coho, chum, steelhead, and cutthroat are supported by Wapato and Hylebos Creeks which enter the waterway (U.S. Army Corps of Engineers, 1976). The bay is used for both sport and commercial salmonid fishing (Figure V-25). Quartermaster Harbor, just opposite the Bay, is a valuable spawning ground for herring and surf smelt (Figure V-27), and is listed (WDOE, 1977-1980) as a critical habitat for cod during winter and spring, as is the adjacent Tacoma Narrows. The Narrows is also critical habitat for the octopus.

Assessments of midwater fish populations (City of Tacoma, 1979), found the dominant community in the Puyallup Waterway composed of dogfish, ratfish, and herring, with lesser numbers of hake, and flat-fishes, midshipman and tomcod. At the time of sampling in August, no salmonids were present. Net tows at the east end of the Bay yielded flatfishes, tomcod and pollock most abundant, followed by ratfish and shiner perch. SCUBA observations in the Tacoma Narrows found the community dominated by the pelagic ratfish and herring, as well as by demersal perches, rockfishes, greenling, and sculpin.

Southern Sound. The inlets of the Southern Sound provide critical nursery areas for juveniles and overwintering areas for adults of herring, gadids, shrimps, and resident salmonids. Beaches within the Southern Sound are the prime spawning habitat within the study area for herring and surf smelt (Figure V-27). The Nisqually River supports runs of chinook, coho, pink, and chum salmon, and the adjacent McAllister Creek supports coho and chum. In addition, the estuary is populated by steelhead, cutthroat, Dolly Varden, and a few sockeye (Fresh et al., 1979). The estuary and river are popular for sport fishing, but are closed to commercial fishing except for an Indian fishery on the lower stretches of the river (Figure V-25). The Nisqually Delta is a critical feeding area for juveniles, along with shallow areas around Anderson Island. Steeper intertidal and shallow subtidal areas, such as DuPont, form migration corridors (Fresh et al., 1979). These areas are also used for rearing by herring, sand lance, and surf smelt (Fresh and Cardwell, 1979).

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Coho and chum salmon, and a few chinook, use the many streams entering the remainder of the Southern Sound (Figure V-25). Low summer flow in many streams forces early downstream migration, making the nearshore and estuarine zones especially important for salmon rearing in this area (Williams et al., 1975). Commercial and sport salmon fishing areas are shown in Figure V-25, along with 3 net-pen rearing sites.

The open midwater habitat has been characterized by herring (Lemberg, 1978), hake, midshipman, pollock, and dogfish in Case and Carr Inlets (Maynard, 1972; Thorne, 1970). Beeson (1976) also noted dominance by dogfish in Eld Inlet. Carr Inlet is a critical habitat for Pandalus jordani (Magoon, 1974; WDOE, 1977-1980).

WDOE (1977-1980) lists the south end of the Tacoma Narrows and the neighboring Fox Island and Hale Passage areas as critical for cod spawning during winter and spring. Sport fishing areas are shown in Figure V-29.

Few data are available on nekton populations in Budd Inlet. Budd Inlet supports runs of chinook, coho, and chum salmon. Beaches in Budd Inlet are heavily used for surf smelt spawning; herring schools are frequently present, but little spawning occurs. The mouth of Budd Inlet is a prime area for Pandalus danae.

Sinclair Inlet and the Port Orchard System. Virtually no nekton data are available from Sinclair Inlet. The lowland streams entering this basin support a few chinook, but mostly coho and chum salmon; net-pen rearing culture of salmon is conducted at the National Marine Fisheries Service laboratory at Manchester (Figure V-25). The basin also has several important herring and surf smelt spawning beaches (Figure V-27). Port Orchard and Eagle Harbor support populations of the shrimp Pandalus danae (Magoon, 1974).

The midwater fish community in Port Orchard, as assessed by trawling, is dominated by herring, tomcod, plainfin mid-shipman, sablefish, ratfish, gadids, surf and longfin smelt, and dogfish (Thorne, 1970; Cooney, 1967). Port Orchard is listed by WDOE (1977-1980) as critical habitat for big and longnose skate.

MAMMALS

Species Assemblages

The number of marine mammal species in Puget Sound is limited by the enclosed and shallow waters, which generally exclude the largest animals. Table V-5 lists the principal species for the entire area, including the Strait of Juan de Fuca. Of these, only the river otter (Lutra) and the harbor seal (Phoca) are resident in the study area; the killer whale (Orcinus) migrates into the region regularly, and the gray and minke whales (Eschrichtius and Balenoptera), Steller's sea lion (Eumetopias), and Dall's porpoise (Phocoenoides) occasionally. Larger species such as the blue whale are sighted rarely (Everitt et al., 1980). Only the first three animals can be considered integral parts of the food web of the Main Basin and Southern Sound. The humpback whale (Megaptera) and harbor porpoise (Phocoena) are thought to have been occasional or resident organisms, but are now apparently depleted within the study area, presumably by human actions (Everitt et al., 1979).

The river otter (Lutra) can be confused with the sea otter (Enhydra lutris), which is absent from Puget Sound, probably was never common, and which has been unable to establish itself when introduced (Everitt et al., 1979 and 1980).

Life Cycles

Mammals are the largest and longest-lived marine animals. In general they breed and give birth once per year or less, bearing one offspring per delivery, and have gestation times of a year or longer. Table V-6 gives life history information for the species. Neither the otter nor the harbor seal is migratory; of the larger mammals, those with fixed seasonal migrations are most likely to enter the study area. Mammals exhibit a long period of immaturity and a high degree of parental care, and are vulnerable to human disturbance (Haley, 1978).

Temporal Abundance

Because of their long life cycles, mammal populations are more stable than those of smaller organisms, especially among non-migratory species. Population estimates can be difficult, however, due to avoidance of humans (Calambokidis et al., 1978).

Harbor seals, formerly considered pests interfering with harvest of salmon and other commercial fishes, were subject to bounty hunting in Washington until 1960. During this time populations declined, and the Southern Sound was a principal hunting area. Indications now are that the amount of food eaten by harbor seals is less than 5 percent of the

TABLE V-5

MAJOR TAXA OF MAMMALS OBSERVED IN PUGET SOUND[a]

Order Carnivora
  Family Mustelidae
        Lutra canadensis pacifica (1b)   River otter

  Family Otaridae
        Zalophus californianus (3)   California sea lion
        Eumetopias jubatus (2)   Northern (Steller's) sea lion

  Family Phocidae
        Phoca vitulina richardsi (1)   Harbor seal
        Mirounga angustirostris (3)   Northern elephant seal

Order Mysticeti
  Family Eschrichtiidae
        Eschrichtius robustus (2)   Gray whale

  Family Balaenopteridae
        Balaenoptera acutorostrata (2)   Minke whale
        Megaptera novaeangliae (3)   Humpback whale

Order Odontoceti
  Family Delphinidae
        Phocoena phocoena (3)   Harbor porpoise
        Phocoenoides dalli (2)   Dall's porpoise
        Lagenorhynchus obliquidens (3)   Pacific white-sided
                                         dolphin
        Orcinus orca (1)   Killer whale

a   Sources: Everitt et al., 1979 and 1980;
              Balcomb and Angell, in press;
              Simenstad et al., 1979.

b   Numbers in parentheses indicate approximate abundance/frequency
    of sitings in the Sound: 1 = common, 2 = occasional, 3 = rare.

TABLE V-6

PUGET SOUND MARINE MAMMAL LIFE CYCLES AND VITAL STATISTICS

Species	Size	Population	Habitat	Migration	Breeding Season	Birth Season
River Otter	1.1-1.3m 8-9kg (a,e)	unknown (a)	estuary subtidal & salt marsh (a,g)	fresh fall marine spring(g)	May June (g)	April May (g)
California Sea Lion	male 2m 270kg; female 1.8m 90kg (a,b)	up to 296 winter, 0 summer (a)	rocks, Northern Sound (a,b)	California & Mexico May-June; British Columbia winter(a,b)	May-June (b)	early summer (b)
Steller's Sea Lion	male 3m, 1000kg; female 2m 300kg (a,b)	up to 259 winter, 0 summer (a,b)	rocks, North Sound (a,b)	coastal islands summer, inshore winter(a,b)	May-June, Northern Sound (a,b)	early summer, Northern Sound (b)
Harbor Seal	2m & 150kg (a,b)	340, Southern Sound (d)	sand bars, rafts, rocks (d)	limited (d)	summer (d)	July-Sept. (a,d)
Elephant Seal	male 5-6m 2000kg; female 2.5m 800kg(a,b)	occasional (a,b)	rocks, North Sound (a,b)	Mexico & California winter; open Pacific summer(b)	Dec.-Feb. (b)	Dec. (b)
Killer Whale	8m, 8000 kg (male) 7m, 4000 kg (female) (a)	80 resident (3 pods); 230 summer (21 pods) (a,b,c)	Open water (a)	pursue food; some offshore migration (a,b,c)	all year; peak summer (a)	winter (b)
Gray Whale	14m, 30 tons (a,b)	occasional (a)	near shore (a,b)	California & Mexico winter; Alaska summer(a)	winter (a,b)	winter (a,b)
Minke Whale	9m 9 tons (a,b)	occasional (a)	banks & bays - North Sound (a,b)	resident (a,b)	unkown	unknown
Humpback Whale	12m 50 tons (a,b)	occasional (a)	open water (a)	Mexico & Hawaii winter; north summer(a,b)	winter (a,b)	winter (a,b)
Harbor Porpoise	1.8m 72kg (a,b)	<100, North Sound (b)	harbors & bays (a,b)	pursue food (b)	late summer (b)	summer (a)
Dall's Porpoise	2m 150kg (a,b)	40-60 Northern Sound (a,c)	open water (a)	pursue food (b)	unknown	unknown
White-sided Dolphin	2.2m 180kg (a,b)	rare (a)	open water (a)	Mexico-B.C. winter; Alaska summer (a)	spring-fall (b)	unknown

References

a. Everitt et al., 1979 and 1980.

b. Balcomb and Angell, in press.

c. Simenstad et al., 1979.

d. Calambokidis et al., 1978.

e. Harris, 1968.

f. Haley, 1978.

g. WDOE, 1977.

commercial fish harvest (Everitt et al., 1979). Seals and other
mammals are now guarded by the Marine Mammal Protection Act of 1972, but
humans are still blamed for most seal mortalities, including possible
reproductive difficulties due to organochlorine pollution (Calambokidis
et al., 1978). Nevertheless, Calambokidis et al. (1978) estimate that
the seal population in the Southern Sound is currently stable.

Seals "haul-out" and rest out of the water part of the day.
At Gertrude Island (Carr Inlet) seals most commonly haul-out twice a day
at low tide; they spend longer out of the water during storms or during
mating. In Eld Inlet, however, seals haul out on log booms at night
only, regardless of tide, possibly to avoid human disturbance. There is
also some variability of pupping times with location. Pups nurse 3 to 6
weeks, during which time the colony may be especially vulnerable to
disturbance (Calambokidis et al., 1978).

Appearances of less common mammals are governed by migration
patterns (Table V-6). Killer, minke and gray whales may enter the study
area during any season; Steller's sea lions enter the Sound in winter;
elephant seals and Dall's porpoises spring through fall (Everitt et al.,
1979 and 1980).

River otters are commercially harvested for their fur on Puget
Sound, but given the encroachment on their habitat by humans, this
likely cannot continue without threatening populations (Everitt et al.,
1979, 1980). Harbor porpoise populations are also suspected to be
declining, due to habitat encroachment and the very shy nature of the
species (Haley, 1978).

Spatial Abundance

Harbor seals remain close to areas in which they can haul-out and
rest between feedings or while giving birth. Recent censuses of harbor
seals (Calambokidis et al., 1978) have revealed previously unknown
haul-out areas in the Southern Sound, and more undiscovered grounds may
exist. Observed haul-out areas are shown in Figure V-30. The spatial
distribution of seals appears to be controlled by availability of
haul-out areas which are 1) protected from approach by land, 2) accessible
to deep water, 3) close to appropriate food, and 4) free from human
disturbance. Although elsewhere in the Sound rocks, sand bars, and salt
marshes provide haul-out substrate, within the study area (except for a
sand/cobble beach at McMicken Island) most hauling out occurs on
man-made rafts, barges, and log booms.

The major known harbor seal colony in the study area is at Gertrude
Island, Carr Inlet. Breeding and pupping occur at all sites, however.
Different sites appear to support genetically distinct populations, with
slightly different pupping times, and with little intermigration or
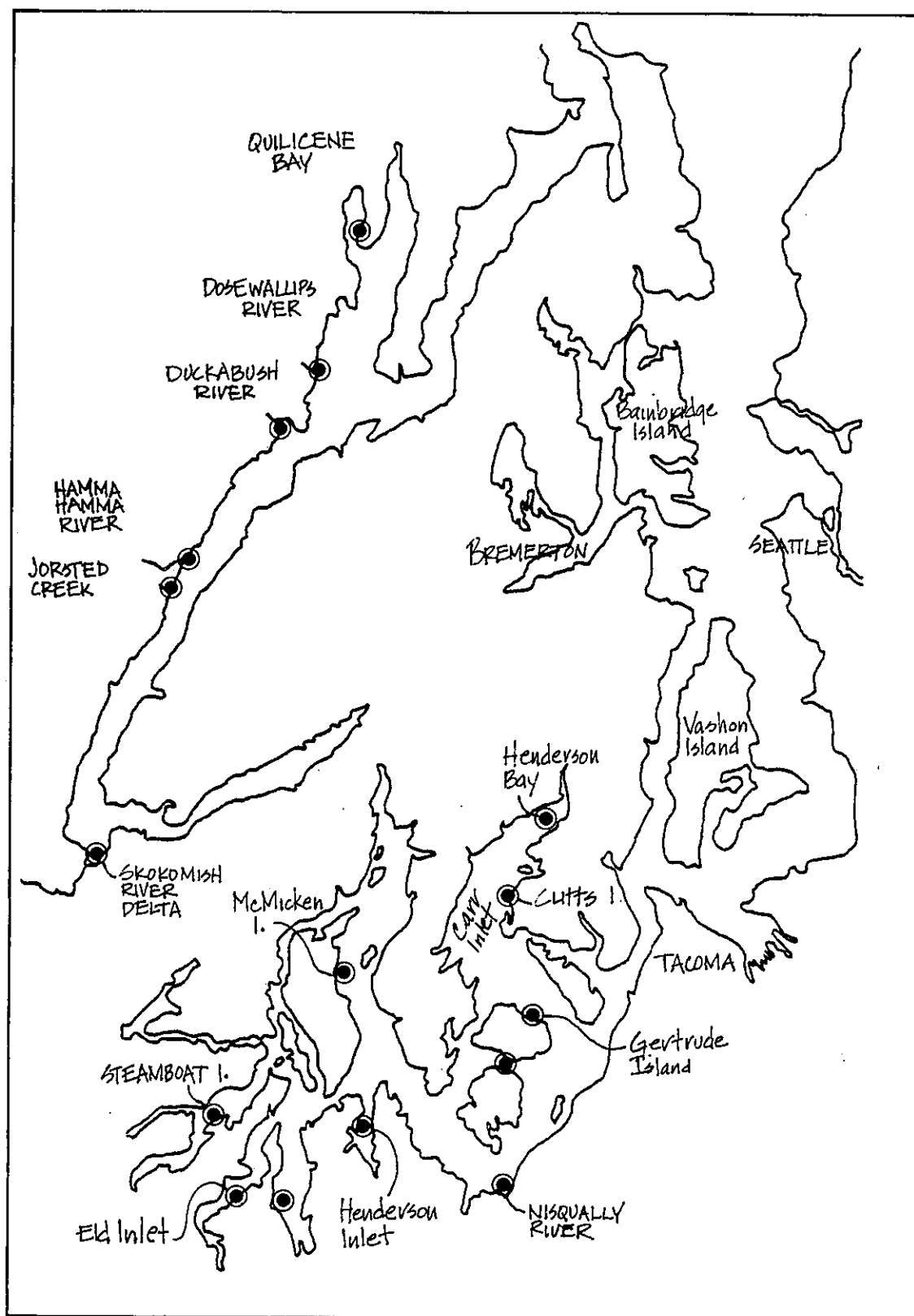
Figure V-30. Seal Haulout Sites in Puget Sound.
Source: Calambokidis et al., 1978; WDOE, 1977 through 1980.

interbreeding. Human harassment apparently causes harbor seals to abandon haul-out areas; this may be the cause for abandonment of the Nisqually Delta region and of Steamboat Island (Calambokidis et al., 1978). WDOE (1977-1980) lists Henderson Bay (Carr Inlet) as a critical habitat for the harbor seal.

Little is known of river otter habits. They can apparently inhabit marine or fresh water habitats exclusively or migrate between. There is no estimate of their abundance in the study area, but observations are widespread (Everitt et al., 1979, 1980). Critical habitats for the river otter, as defined by WDOE (1977-1980), are shown with locations of sightings in Figure V-31.

Killer whales and harbor and Dall's porpoises migrate in groups. Harbor porpoises remain roughly within the 20 m isobath, close to shore (Haley, 1978).

PELAGIC MARINE BIRDS

As was the approach taken with the fish, the information on the birds in the study area is divided into two groups. The first, presented here, considers those species which reside and feed predominantly offshore. Those birds that are primarily dependent on the shore and/or the shallow bottom are included in Chapter 6. Data germaine to this report are very limited at this time, but support the following observations.

Species Assemblage

The variety of marine birds which utilize Puget Sound, at least on a seasonal basis, is presented in Table V-7.

Life Cycles

The majority of the offshore feeding birds are migrants that overwinter in the protected waters of Puget Sound, but breed in other areas as part of a normal migratory cycle. The details of these cycles are complex and vary among species. This information is beyond the scope of this report and can be found in other references (Eaton, 1975; Salo, 1975; WDOE, 1977). The pigeon guillemot is the only species for which nests (in Elliott Bay) have been observed in the study area. However, other species, particularly those observed year-round such as the common merganser, may also nest in this area (Salo, 1975).
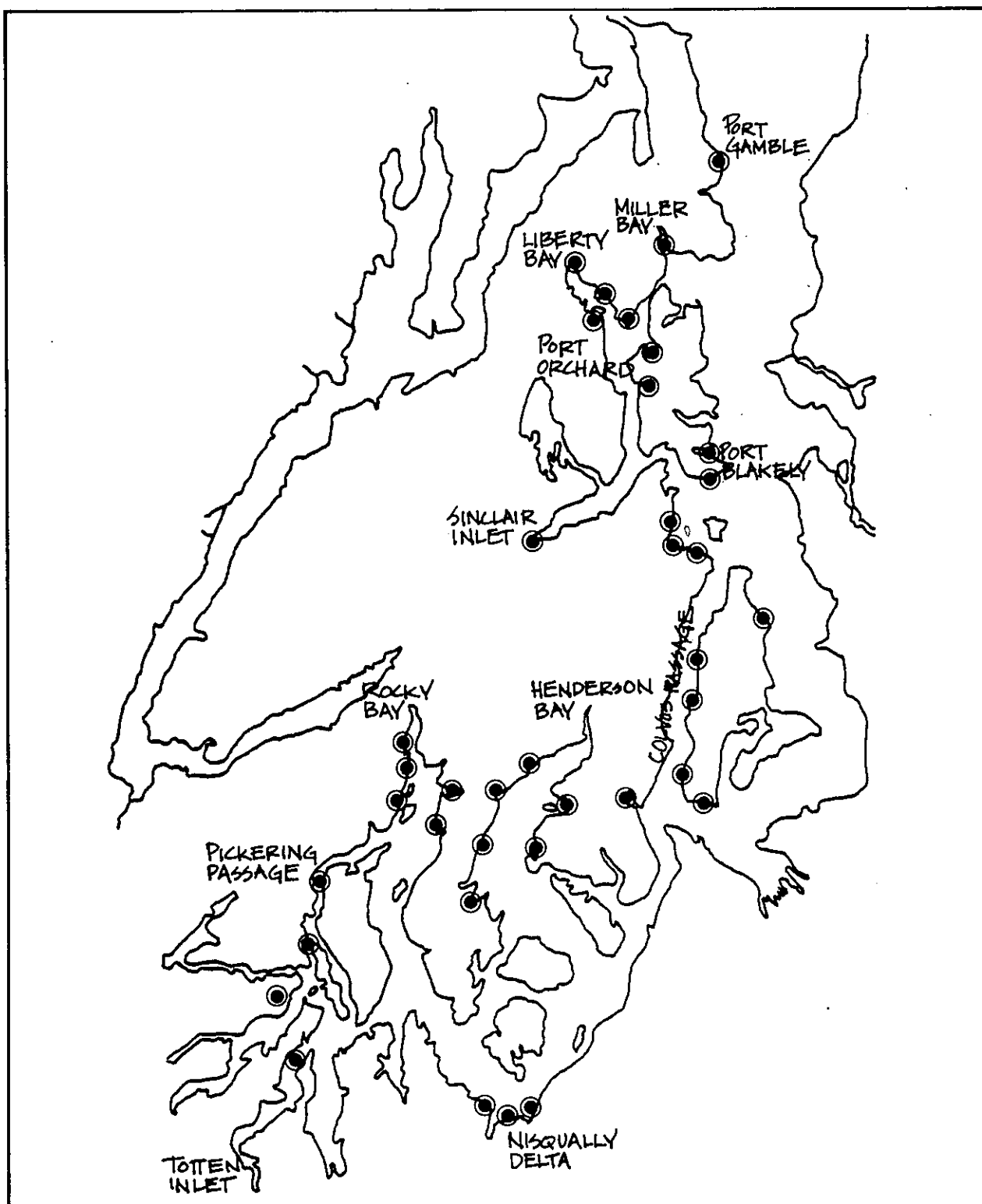
Figure V-31.   Known River Otter Habitats in Puget Sound

Source: WDOE, 1977 through 1980; Everett et al., 1980.

Temporal and Spatial Distributions

No recent population studies on birds within the Main Basin and/or Southern Puget Sound could be located during the preparation of this report (D. A. Manuwal, Forestry Resources, University of Washington and R. Hirschi, Washington Department of Game, personal communications). A multi-year, semi-quantitative survey from ferry-boat observations has been performed but the data have not been assembled or analyzed at this time (R. Hirschi, personal communication). Similarly, the local chapters of the Audubon Society have performed winter surveys (Christmas Day) in Elliott and Commencement Bays and Budd and Sinclair Inlets for a number of years but these data have not been compiled into a useful form.

The seasonal occurrences of the birds has also been included in Table V-7. As noted above, most of these species are solely winter residents (Salo, 1975), but a few species, noted in the table, are fall and spring migrants. The California, ring-billed, and new gulls and the pigeon guillemot and Cassin's auklet have been observed from fall to spring. Only the harlequin duck and common merganser have been observed year-round (Salo, 1975).

Three species, the red throated loon, western grebe, and double-crested cormorant, are listed on the Audubon Society's Blue List of species whose abundance in all or part of their range is decreasing (Eaton, 1975). No studies were identified which indicated the cause(s) of these decreases. All three of these species are winter residents in Puget Sound.

The observed spatial occurrences of the marine birds in the four embayments of the study area are also included in Table V-7. As would be expected for a highly mobile organism, most species have been observed in all four embayments.

The major food sources for pelagic birds are small fish, molluscs, and crustaceans. In addition to these prey, the Anatidae feed on polychaetes, eelgrass, grains, seeds, and sedge. No estimates, however, have been made of the importance of the pelagic birds on the ecosystems of Puget Sound.

TABLE V-7. SELECT PELAGIC MARINE (OFFSHORE) BIRDS OF PUGET SOUND

Family	Common Name	Scientific[1]	Location[2] E	C	B	S	Season[2] F	W	Sp	Su
GRAVIIDAE	Common loon	Gavia immer	X	X	X	X				X
	Arctic loon	Gavia arctica	X	X						X
	Red throated loon (3)	Gavia stellata	X	X						X
PODICIPEDIDAE	Red-necked grebe	Podiceps grisegena	X	X						X
	Horned grebe	Podiceps auritus	X	X	X	X				X
	Eared grebe	Podiceps caspicus	X	X	X	X				X
	Western grebe (3)	Aechmophorus occidentalis	X	X	X	X				X
PHALACROCORACIDAE	Double-crested cormorant (3)	Phalacrocorax auritus	X		X	X				X
	Brandt's cormorant	Phalacrocorax penicillatus	X	X		X				X
	Pelacic cormorant	Phalacrocorax pelagicus	X	X		X				X
ANATIDAE	Western Canada goose	Branta canadensis occidentalis	X	X						X
	Black brant	Branta nigricans	X	X						X
	White-fronted goose	Anser albifrons	X						X	X

Family	Common Name	Scientific[1]	Location[2] E	C	B	S	Season[2] F	W	Sp	Su
	Pintail	Anas acuta	X	X					X	X
	American wigeon	Mareca americana	X	X				X		
	Northern Shoveler	Spatula clypeata	X	X				X		
	Canvasback	Aythya valisineria	X	X				X		
	Greater scaup	Aythya marila	X	X	X	X		X		
	Lesser scaup	Aythya affinis	X	X				X		
	Common goldeneye	Bucephala clangula		X	X	X		X		
	Barrow's goldeneye	Bucephala islandica	X	X	X	X		X		
	Bufflehead	Bucephala albeola		X		X		X		
	Oldsquaw	Clangula hyemalis	X	X		X		X		
	Harlequin Duck	Histrionicus histrionicus		X		X	X	X	X	X
	White-winged scoter	Melanitta deglandi	X	X		X		X		
	Surf scoter	Melanitta perspicillata	X	X	X	X		X		
	Black scoter	Melanitta nigra	X	X		X		X		
	Common merganser	Mergus merganser americanus	X	X		X	X	X	X	X
	Red-breasted merganser	Mergus serrator	X	X		X		X		

TABLE V-7. CONTINUED

Family	Common	Scientific[1]	Location[2] E	C	B	S	Season[2] F	W	Sp	Su
STERCORARIIDAE	Parasitic jaeger	stercorarius parasiticus	X						X	X
LARIDAE	Glaucous-winged gull	Larus glaucescens	X	X	X	X	X			
	Western gull	Larus occidentalis occidentalis	X	X			X			
	Herring gull	Larus argentatus	X	X			X			
	Thayer gull	Larus thayeri	X				X			
	California gull	Larus californicus	X	X			X	X	X	
	Ring-billed gull	Larus delawarensis	X	X			X	X	X	
	Mew gull	Larus canus	X				X	X	X	
	Bonaparte's gull	Larus philadelphia	X	X	X	X	X	X		
	Common tern	Sterna hirundo hirundo	X				X	X		
ALCIDAE	Common murre	Uria aalge californica	X	X	X		X			
	Pigeon guillemot	Cepphus columba	X	X	X		X	X	X	
	Cassin's auklet	Ptychoramphus aleutica	X	X			X	X	X	
	Marbled murrelet	Brachyramphus marmoratus marmoratus	X	X			X			
	Rhinoceros auklet	Cerorhinca monocerata	X	X		X	X			

FOOTNOTES:

(1) Reference: Larrison and Sonnenberg (1968)

(2) Reference: Salo (1975)   E - Elliott Bay   F - Fall
                               C - Commencement Bay   W - Winter
                               B - Budd Inlet   Sp - Spring
                               S - Sinclair Inlet   Su - Summer

(3) Included on Audubon Society's "Blue List" (U.S. Army Corps of Engineers, 1975)

(4) Nest sites observed (Salo, 1975)

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SUMMARY: PELAGIC BIOTA

The pelagic biota of Puget Sound are classified as phytoplankton, zooplankton, nekton, mammals, and birds. The phytoplankton is dominated by diatoms, with notable appearances by dinoflagellates in summer, especially in protected inlets. Little is known about nanoflagellates, which may compose an important alternate floral community. Annual primary production averages 465 gC/m^2/yr at a representative station in the Main Basin, and less in the Southern Sound. This productivity, which is high for coastal areas at this latitude, is attributed to contemporaneous upwelling and surface stability. The Main Basin is characterized by a series of intermittent blooms from May through September, occasioned by the coincidence of high insolation, high surface stability, and reduced flushing. The same factors operate in the rest of the Sound, with evidence that productivity suffers due to nutrient depletion in embayments during summer, but begins earlier in the spring.

Phytoplankton species composition may be linked to hydrography. Puget Sound exhibits a high degree of heterogeneity in phytoplankton standing stock on all spatial and temporal scales, which has implications both for data interpretation and for the support of higher trophic levels.

The zooplankton comprises a tremendous diversity of animals, including the temporary presences of meroplanktonic larvae. The dominant organisms in all areas, based on a small number of studies, appear to be the copepod and euphausiid crustaceans which graze primarily on the dominant diatoms of the phytoplankton. The few data available suggest that microzooplankton (primarily ciliate protozoa) and small copepods (the numerically dominant zooplankters) also constitute an important food web link by consuming smaller phytoplankton. Larger copepods and herbivorous micronekton (the dominant zooplankton in terms of biomass) are believed to overwinter at depth and in embayments, and to synchronize their nearsurface spring and summer feeding and egg-laying with abundance of larger diatoms. Data are insufficient to examine possible similar synchronization of meroplankton. The larger zooplankton in particular exhibit a high degree of temporal and spatial heterogeneity, as indicated by the presence of an acoustic scattering layer and of diel and seasonal vertical migrations.

The nekton includes the baitfishes which are relatively small and found nearshore and at shallow depths, midwater animals which live deeper in the water as adults, and salmonids which spawn in fresh water and have a migratory cycle taking most of them into the open Pacific. Life cycle, migratory, and gut content data indicate that nekton can be operationally classified, to first approximation, according to their size alone. Animals less than roughly 60 mm in length, including larvae

of all groups and juvenile baitfish, remain nearshore and alternate in association between the bottom and the water column. Animals up to roughly 200 mm in length, including juvenile salmonids and midwater nekton and adult baitfish, may be found in open waters of the Sound in a fully pelagic niche. Larger adult salmon principally become pelagic in the open Pacific, while other midwater nekton largely remain in the Sound with a variable degree of association between the water column and the bottom.

Diel and seasonal migrations of nekton loosely parallel those of larger zooplankton. In particular, fishes are found nearshore and in embayments during winter and early spring, and move offshore through the summer. This poses an intriguing avenue for research on the spatial and temporal correlations between predators and prey. It would also be valuable to test the assumption that animal behaviors and trophic interactions may be predicted from sizes.

Nearshore and estuarine zones are particularly vulnerable habitats for nekton, since these are the areas in which sensitive juveniles congregate during spring. These animals are dependent on the shallow epibenthic habitat, unlike more mature animals which are free to seek a wider possible range of pelagic habitats. This is also a critical stage in which food abundance has a direct relationship to juvenile survival.

During maturation and offshore migration, it appears that nekton depend on copepods and euphausiids, which in turn depend on diatom blooms. Greve and Parsons (1977) hypothesize that this food chain may be most vulnerable to pollution owing to the sensitivity of diatoms to many toxic chemicals.

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CHAPTER 6. BENTHIC BIOTA

BENTHIC FLORA

Species Assemblages

The marine benthic flora assemblages of Puget Sound are diverse:
Thom (1978) reporting 157 species; Harlin (1969) 72 species;
Phillips and Fleenor (1970) 125 species. These assemblages may be
divided into three general groups: 1) the seagrasses, primarily eelgrass;
2) benthic microphytes, including the diatoms and blue-green algae; and
3) the macroalgae, including green, red and brown algae. The role of
seagrass and other flora groups in the benthic community is to stabilize
bottom sediments, increase deposition, enhance nutrient transfer,
provide substrate for epiphytic species, provide detritus for inverte-
brate fauna, and to provide cover and protection for numerous fauna
(Phillips, 1972; Thayer and Phillips, 1977). Table VI-1 lists some of
the common species of intertidal and shallow subtidal macroalgae,
seagrasses and microphytes of the Main Basin. Red algae species outnumber
the green algal species almost 2:1, with brown algae, microphytes and
seagrasses having fewer species than the greens. Massive and foliose
species (Table VI-1) are predominantly the green and brown macroalgae.
Both brown and red macroalgae have common species which are perennials.
Habitats range from high intertidal to subtidal with several species
being present throughout the tidal range.

Life Cycles

Life cycles of the benthic flora of Puget Sound vary considerably;
many of them being complex with their details poorly understood
(Mumford, in press). Figure VI-1 summarizes the life cycles of select
benthic flora which are representative of several Puget Sound species.
A common seagrass of Puget Sound is the eelgrass Zostera marina, which
can reproduce two ways: 1) vegetatively and 2) through seed dispersal.
Phillips (1972) reports that geographical dispersal of eelgrass is
primarily by seeds rather than vegetative; however, vegetative growth
from rhizomes is the more important reproductive mechanism for local
eelgrass bed maintenance.

The microphytes reproduce by several mechanisms including vegetative
growth, asexual spore reproduction, and sexual auxospore reproduction.
Vegetative reproduction by fragmentation is widespread in the Cyanophy-
cophyta, and asexual reproduction also takes place by production of a
number of different kinds of spores. Baccillariophycophyta undergo

TABLE VI-1

COMMON BENTHIC PLANTS RECORDED AT MAIN BASIN
BEACHES BY THOM ET AL. (1976)[1]

	Total Number of Species Recorded for Phyla	Massive and Foliose Species[4]	Habitat[2]
<u>SEAGRASS</u>	1		L
<u>Zostera marina</u> Lamouroux			
<u>MICROPHYTES</u>			
Cyanophycophyta (blue-green algae)	7		
Baccillariophycophyta (diatoms)	4		
<u>Odontella aurita</u> (Lyngbye) C.A. Agardh			L
<u>MACROALGAE</u>			
Chlorophycophyta (green algae)	40		
<u>Enteromorpha intestinalis</u> (Linnaeus) Link var. <u>intestinalis</u>			H M L
<u>Enteromorpha linza</u> (Linnaeus) J. Agardh		X	M L
<u>Spongomorpha saxitilis</u> (Ruprecht) Collins var. <u>saxitilis</u>			H M L
<u>Ulva expansa</u> (Setchell) Setchell and Gardner			L S
<u>U. fenestrata</u> Postels and Ruprecht		X	M L
<u>U. lactuca</u> Linnaeus var. <u>lactuca</u>		X	H M L
Phaeophycophyta (brown algae)	27		
<u>Colpomenia bullosus</u> (Saunders) Yamada			M L

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TABLE VI-1 (Continued)

	Total Number of Species Recorded for Phyla	Massive and Foliose Species[4]	Habitat[2]
C. peregrina (Sauvergeau) Hamel			H M
Fucus gardneri Silva		X,P	H M L S
Laminaria saccharina (L.) Lamoroux[3]		X	L S
Nereocystis luetkeana (Mertens) Postels and Ruprecht		X	L S
Petalonia fascia (O. F. Mueller) Kuntze		X	M L
Ralfsia pacifica Hollenberg in Smith			H M L
Sargassum muticum (Yendo) Fensholt [3]		X,P	M L
Scytosiphon lomentaria (Lyngbye) J. Agardh		X	M L
Rhodophycophyta (red algae)	78		
Antithamnionella glandulifera (Kylin) Wollaston			L S
Caulacanthus ustulatus (Mertens and Turner) Kuetzing			H
Ceramium eatonianum (Farlow) DeToni			H
Cryptosiphonia woodii J. Agardh			H M L
Gigartina exasperata Harvey and Bailey		X,P	L
Gigartina papillata (C. Agardh) J. G. Agardh in C. Agardh		X,P	H M L S
Hildenbrandia prototypus Nardo			M L S
Iridaea cordata (Turner) Bory subsp. cordata		X,P	

TABLE VI-1 (Continued)

	Total Number of Species Recorded for Phyla	Massive and Foliose Species[4]	Habitat[2]
Iridaea heterocarpa Postels and Ruprecht			M L
Odonthalia flocosa (Esper) Falkenberg			H M L
Palmeria palmata (Linnaeus) Stackhouse			M
Polysiphonia paniculata Montagne			L
Porphyra abbottae Krishnamurthy			H M L
Porphyra miniata (C. Ag.) C. Agardh			M L
Porphyra perforata J. Agardh f. _perforata_			H
Pterosiphonia bipinnata var. _bipinnata_ (Postels and Ruprecht) Falkenberg			H M L
Rhodomela larix (Turner) C. Agardh			H M L
Scagelia occidentale (Kylin) Wollaston			S

(1) Condensed from Thom et al. (1976) to list only those species with >6 percent frequency of occurrence during any one season throughout the year. Five beaches were Richmond Beach, Carkeek Park, West Point, Alki Point, and Lincoln Park. Sampling stations shown in Figure VI-2 map.

(2) H = high intertidal: found at >+5 ft. (1.5 m) above MLLW.
M = mid intertidal: found from +2 ft. (0.7 m) to +4 ft (1.2 m) above MLLW.
L = low intertidal: found from -1 ft. (0.3 m) below MLLW to +1 ft. (0.3 m) above MLLW.
S = subtidal: found -2 ft. (0.7 m) below MLLW and deeper.

(3) Dominant species by size or frequency of occurrence listed by Thom (1978), additional to Thom et al. (1976).

(4) X = Massive and foliose species reported by Thom et al. (1976); P = Perennial.
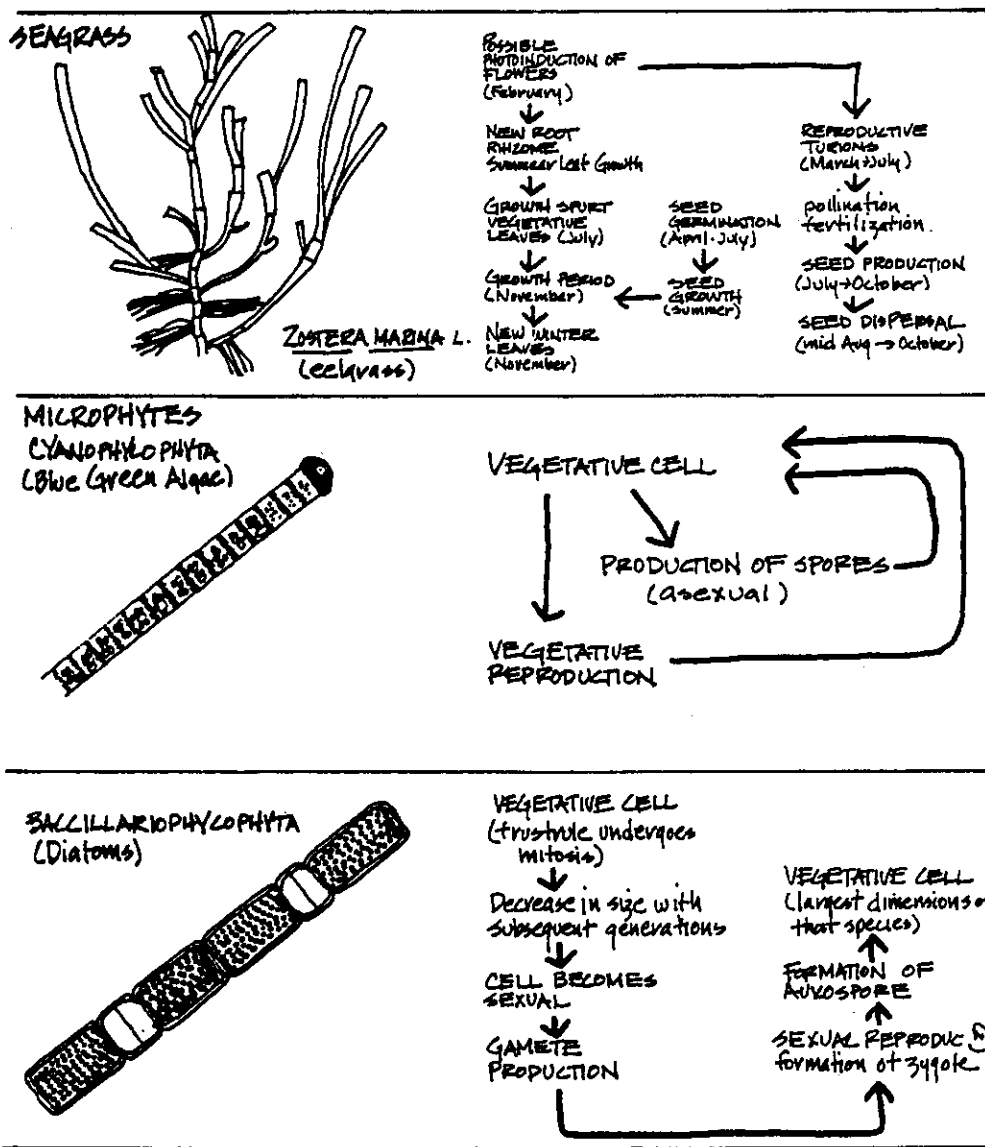
Figure VI-1. Life Cycles of Select Benthic Flora in Puget Sound.

Top panel (Green Algae):

(Green Algae)
CHLOROPHYCO-
PHYTA
(mature
sporophyte)
ULVA sp.

ALTERNATION OF ISOMORPHIC GENERATIONS

SPOROPHYTE (conspicuous asexual phase)
↓
MATURITY (formation of spores)
↓
RELEASE OF MICROSCOPIC SWIMMING SPORES
↓
GERMINATION OF SPORES

YOUNG SPOROPHYTE
↑
SEXUAL REPRODUCTION (formation of zygote)
↑
PRODUCTION OF GAMETES
↑
GAMETOPHYTES (conspicuous sexual stage)

Middle panel (Brown Algae):

PHAEOPHYCO-
PHYTA
(mature
sporophyte)
NEREOCYSTIS sp.
(Brown Algae)

ALTERNATION OF HETEROMORPHIC GENERATIONS

SPOROPHYTE GROWTH (conspicuous asexual phase)
↓
MATURITY (formation of sporangia)
↓
RELEASE OF MICROSCOPIC SWIMMING SPORES
↓
SPORES SETTLE TO BOTTOM and GERMINATE

YOUNG SPOROPHYTE
↑
SEXUAL REPRODUCTION (zygote formed)
↑
♂ GAMETOPHYTE ♀ (microscopic sexual stage)

Bottom panel (Red Algae):

RHODOPHYCOPHYTA
(mature
tetrasporophyte)
Red Algae

ALTERNATION OF ISOMORPHIC GENERATIONS WITH TWO SPORE PRODUCING STAGES

TETRASPOROPHYTE GROWTH (conspicuous asexual phase)
↓
MATURITY (formation of tetraspores)
↓
RELAX and SETTLING OF TETRASPORES
↓
♂ MACROSCOPIC ♀ GAMETOPHYTES (conspicuous sexual stage)

YOUNG TETRASPOROPHYTE
↑
SEXUAL REPRODUCTION formation of carpospores

IRIDAEA CORDATA (red algae)

Figure VI-1 (Cont'd). Life Cycles of Select Benthic Flora in Puget Sound.
Source: Phillips, 1972; Mumford, in press.

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mitotic division and the formation of daughter cells which result in a progressively smaller average cell size in a population. Cells, usually approaching 30 to 40 percent of maximum size, undergo sexual reproduction to eventually produce a vegetative cell which has the largest dimensions of the particular species.

The macroalgae generally go through an alteration of sexual and asexual generations. In some instances, only one generation is conspicuous, differing in appearance considerably from the other (e.g., Nereocystis). In other species, the two generations are quite similar (e.g., Ulva).

Temporal Changes

Temporal changes in the benthic flora of Puget Sound have been documented by Thom (1980, 1978), Thom et al. (1976), Phillips (1972) Harlin (1969), and Neushul (1967).

Thom (1980) documented temporal changes in three benthic flora parameters, 1) species composition, 2) number of species, and 3) percent cover in low littoral rocky substrate in the Main Basin over a two-year period. Table VI-2 shows the temporal change in species composition for those species that comprised at least 5 percent of the algal cover at MLLW. Species composition was affected by changes in water temperature and by a desiccation/cold stress factor based on air temperature and emergence time. In the spring, the species composition consisted of brown and red algae and diatoms. In the summer, green algae dominated, with low intertidal areas having dense mats. The bulk of the winter species composition was comprised of perennial red and brown algae.

The total number of algal species was highest in the spring and correlated with low temperatures and increased sunlight. Figure VI-2a shows the similarity in temporal changes in the number of taxa within the red, green, and brown macroalgae.

Figure VI-2b shows the temporal change in percent algal cover with values highest in the summer and autumn and lowest in the winter. Percent algal cover was positively correlated with sunlight and air temperature and negatively correlated with precipitation (Thom, 1980).

Figure VI-3 shows the temporal change in total dry weight of eelgrass at three Alki Point stations. Maximum values occur in June through September. The total annual eelgrass production for Puget Sound has been estimated to be from 8.4×10^7 to 4.85×10^8 kg (total dry weight) by Phillips (1972). Productivity rates for the eelgrass Zostera marina range from 0.7 to 4.0 gC/m^2/yr.

TABLE VI-2

SEASONAL OCCURRENCE OF MAIN BASIN BENTHIC FLORA
WITH $\geq$5 PERCENT COVERAGE[1]

Month of Percent Cover >5%

Species	Taxa[2]	1974		1975				1976	
		Jly	Oct	Jan	Apr	Jly	Oct	Jan	Apr
Enteromorpha linza	G	●	●			●	●		
Ulva expansa	G						●		●
Ulva fenestrata	G	●	●			●	●		
Ulva lactuca	G	●	●		●	●			
Ceramium washingtoniense	R		●						
Gigartina papillata	R	●							
Pterosiphonia bipinnate	R			●	●				
Baccillariophycophyta	D				●				●

(1) Condensed and modified from Thom (1980) - MLLW data only.

(2) G = green algae (Chlorophycophyta)
    R = red algae (Rhodophycophyta)
    D - diatom (Baccillariophycophyta)

Figure VI-2. Temporal Change in Benthic Flora Parameters in the Main Basin. Source: Thom, 1978.
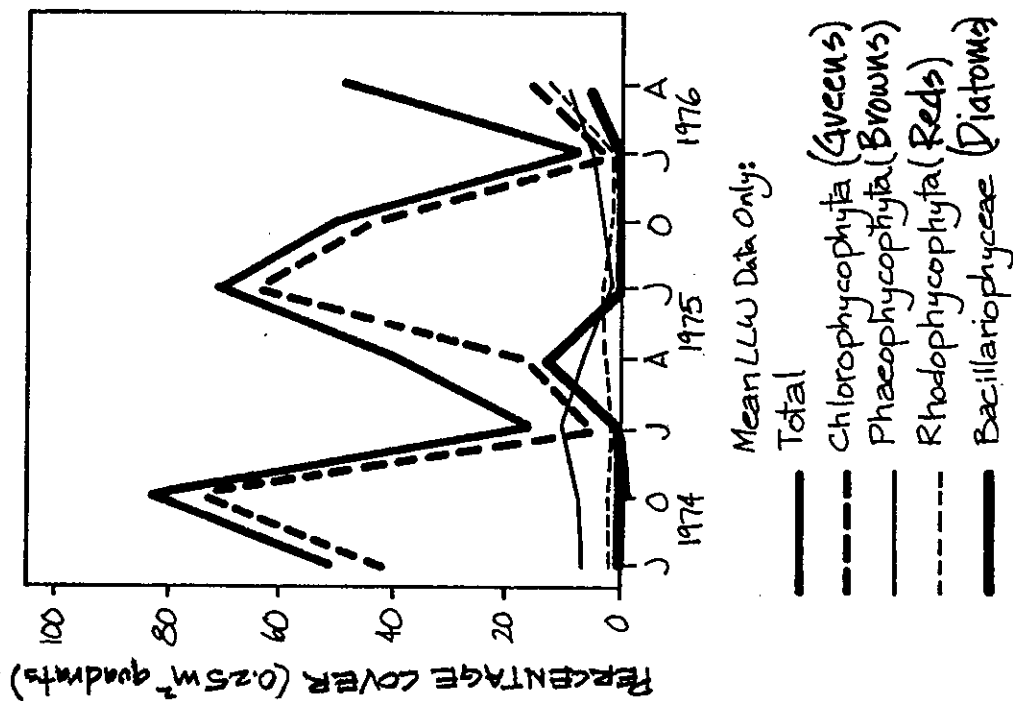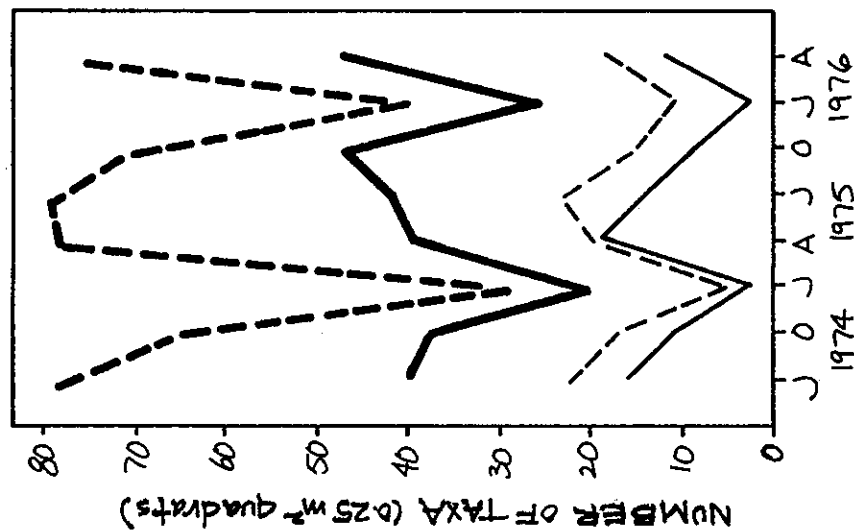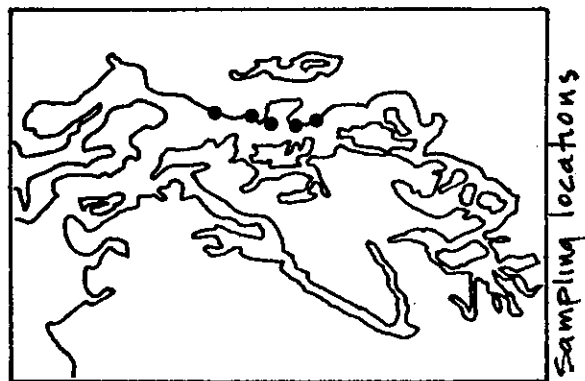
(A) Seasonal Change in no. of Macroalgal Taxa over all beaches. All intertidal heights.

(B) Average Algal Cover Each Season MLLW data only.
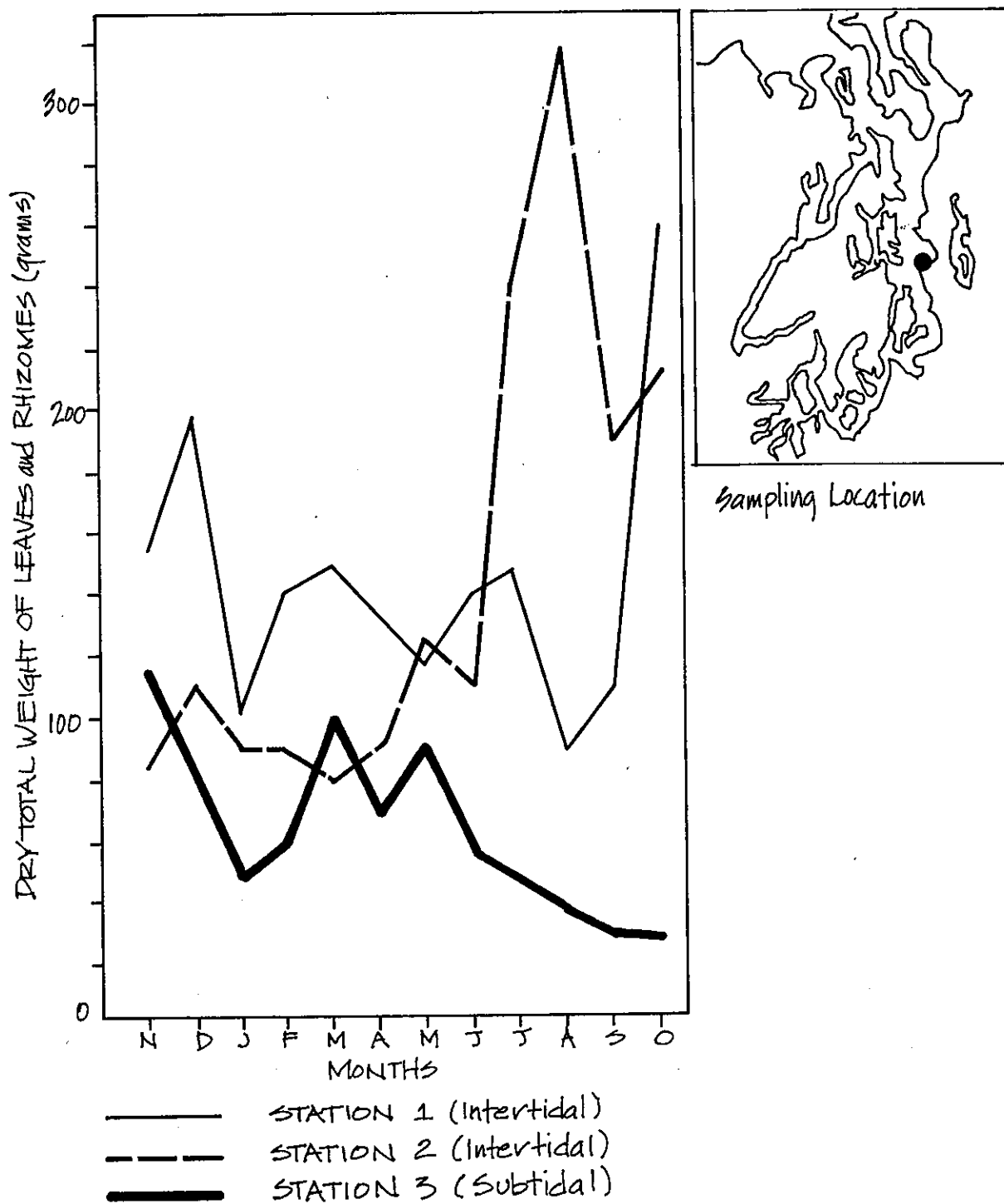
Figure VI-3. Temporal Change in Standing Stock of Eelgrass at Alki Point. Redrawn from Phillips, 1972.

Spatial Changes

Two aspects of spatial variation will be discussed, vertical zonation at particular sites and differences between sites within Puget Sound.

Neushul (1967), graphically documented vertical zonation of benthic flora for several transects in the San Juan Islands. Figure IV-4 compares the vertical zonation patterns for predominantly rock, mud, and mixed substrate transects. Vertical zones of benthic flora are evident in Figure IV-4. For example, low intertidal and shallow subtidal zones tend to have larger, more conspicuous and foliose flora.

Thom et al. (1976) stated that benthic flora in Puget Sound attain their highest percent cover, number of species, and biomass in the low intertidal zone (MLLW).

The lower limit of growth varies between species. For example, the lower growth limit of eelgrass (Zostera marina) is -6.6 m and is presumably limited by light below this depth (Phillips, 1972). Phillips and Fleenor (1970) also hypothesized that light is a controlling factor for sublittoral zonation in Hood Canal. Eelgrass density (plants per m^2) was found to be much greater in the intertidal zone, while biomass (weight per m^2) between intertidal and subtidal areas was similar.

Vertical zonation also may shift seasonally. Algal populations occupied a higher position in the intertidal area in winter than in spring, as reported by Mumford (1973) for the San Juan Islands. He hypothesized this was related to less desiccation during winter due to lower temperature and less sunlight. During winter, low tides occur at night compared to midday occurrence in summer.

On the topic of differences between sites within Puget Sound, several factors have been hypothesized for controlling the benthic flora community. These include: 1) substrate composition, 2) substrate stability, 3) emergence time, 4) temperature changes, and 5) salinity changes. Thom (1978) reported that the benthic flora community was structured by emergence time and substrate composition. Substrate stability was also of primary importance in regulating species composition and percent cover with coarser substrate resulting in fewer number of species and lower percent cover. Similarly, benthic microphyte growth in Main Basin intertidal areas was related to emergence time and temperature changes. Phillips and Fleenor (1970) hypothesized that decreased salinities due to spring runoff limited littoral algal growth in Hood Canal, possibly being detrimental to spore germination.

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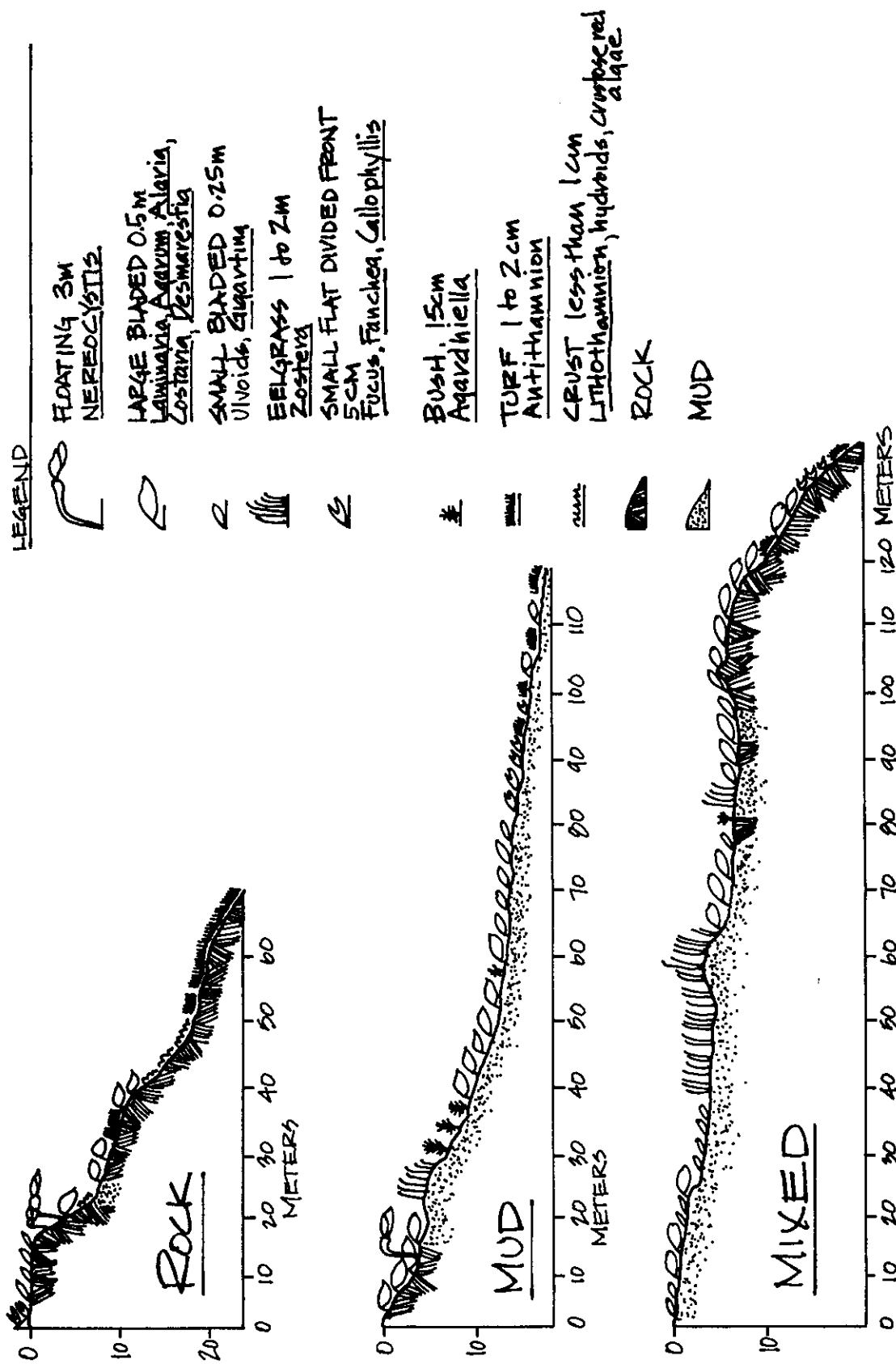
Figure VI-4. Typical Vertical Zonation of Marine Flora on Different Substrates and Slopes in the San Juan Islands.

Modified from Neushul, 1967.

Descriptions of particular plant community assemblages for Puget Sound have been provided by only a few researchers. Neushul (1967) described three plant assemblages for San Juan Island: 1) a _Laminaria_ association in shallow waters, 2) an _Agarum_ zone dominating at mid-depths, and 3) a red algal association at depths of 17 to 20 meters.

Thom (1978) analyzed benthic flora of the Main Basin by numerical analysis. He conducted cluster analysis for the predominant species using percent cover data. This resulted in the definition of 10 species groups (Table VI-3). The most dense and apparently ubiquitous groups consisted of _Ulva_ species associated with barnacles and mussels (group 9) and several red algal species (group 10). Thom (1978) also defined 10 habitat types for the main basin and documented the average percent cover for each of the predominant species (Table VI-3).

Thom (1978) further described this benthic flora community of the eastern shore of the Main Basin as relatively unproductive. Variation in physical factors by season and the lack of suitable habitat favored ephemeral, opportunistic species over stable slow-growing species in this area. At specific sites along the eastern shore, Thom (1978) documented high variability as evidenced by the subtidal communities between West Point and Lincoln Park beaches. He hypothesized that the difference in community structure between these sites was caused by reduced water clarity at West Point.

Spatial differences in benthic flora communities between southern Puget Sound and other areas of Puget Sound were noted by Harlin (1969) in sampling at Steamboat Island, located at the entrance to Totten Inlet. Absent from the flora were red algae (_Endocladia, Odonthalia_), siphonous green algae, the kelp _Nereocystis luetkeana,_ and the seagrasses _Zostera_ (eelgrass) and _Phyllospadix._ The lack of eelgrass in western portions of southern Puget Sound was also documented by Phillips (1972). The spatial occurrence of eelgrass in Puget Sound is shown in Figure VI-5. About 9 percent, or over 125,000 acres, of the bottom of Puget Sound is covered by eelgrass (Thayer and Phillips, 1977). No eelgrass beds were documented for Elliott or Commencements Bays, Sinclair or Budd Inlets; however, they do seem to occur at the entrances with the exception of Budd Inlet. Eelgrass was reported during a 1962-1963 survey as absent west of a line from the Nisqually Flats to Henderson Bay. Phillips (1972) listed optimum chemical and physical conditions for eelgrass in Puget Sound as: 1) salinity 27 to 34⁰/oo; 2) temperature 7.5 to 12.5|C; 3) depth -1 to -4 m below MLLW; 4) substrate of muddy sand; 5) current velocity $\leq$ 3.5 knots. Of these conditions, low salinity was hypothesized as one reason for the spatial difference in eelgrass occurrence. Another reason suggested was high turbidity from unspecified sources (presumably plankton). For the other species listed above, the reasons for their absence is unknown. However, lack of suitable substrate was rejected as a reason by Harlin (1969).
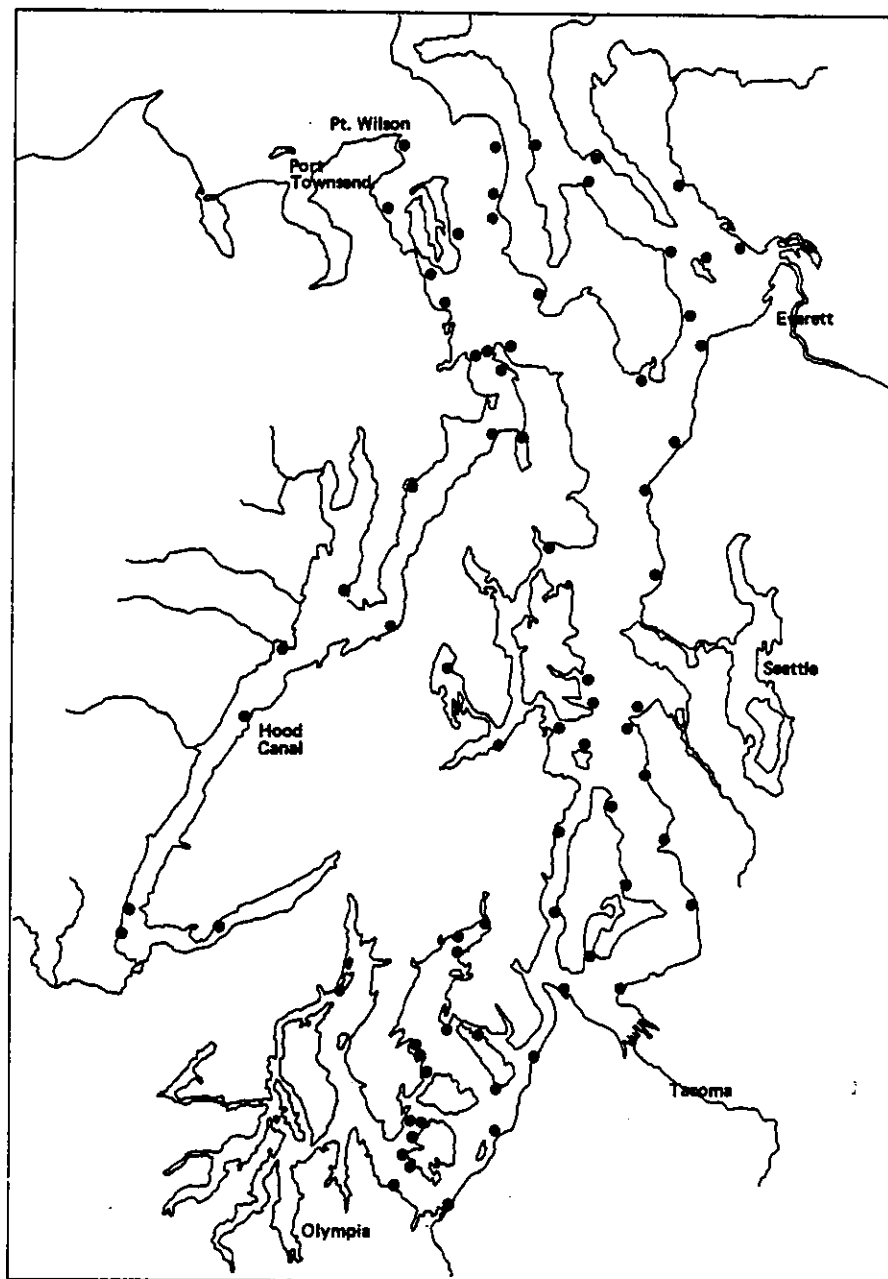
● OCCURRENCES OF Zostera marina

Figure VI-5. Geographic Spatial Occurrence of Eelgrass in Puget Sound

Source: Phillips, 1972.

TABLE VI-3

AVERAGE COVER VALUES OF MAIN BASIN HABITATS
FOR THE 40 MOST ABUNDANT SPECIES

Modified from Thom (1978)[1]

(1) Combination of Tables 12 and 13 from Thom (1978).

(2) Defined by cluster analysis - See Thom (1978).

KEY

Average percent cover
● > 5.0
● 0.5 - 5
● 0.1 - 0.4

D — Diatoms
C — Green Algae
P — Brown Algae
R — Red Algae
I — Barnacle (animal)
-II — Mussel (animal)
III — Sea anemone (animal)

		Habitat	A	B	C	D	E	F	G	H	I	J
		Other			pooling		pooling		pooling			
		Slope	high	low	low	low	low	low	low	low-mid	mid-low	high
		Tidal Height	mid-low	low	high	mid	high-mid	low	mid-low	high-mid	mid	high
		Substrata	stable cobble	rock shelf	relatively stable	sand	gravel	sandstone bench	sandy with cobble	gravel	gravel	gravel
Species Group (2)	**Taxa**											
1 Chaetomorpha	C		●		●							
Petalonia	P		●	●			●	●	●	●		
Ceramium	R				●			●	●			
Caulocanthus	R				●							
Ulva sp.	C		●		●							
2 Iridaea cordata	R		●	●					●			
Antithamnionella	R		●	●								
Polysiphonia paniculata	R		●	●	●							
3 Laminaria saccharina	P		●									
Leathesia	P		●		●						●	
4 Colpomenia	P							●	●			
Odonthalia washingtoniensis	R								●	●		
Neoagardhiella	R								●		●	
5 Porphyra torta	R						●					
6 Desmarestia aculeata	P		●				●					
Ulva expansa	C		●						●			
7 Monostroma sp.	C		●	●	●	●		●	●			●
Spongomorpha sp.	C		●	●	●			●	●	●	●	●
Iridaea heterocarpa	R		●	●	●				●	●	●	●
Enteromorpha intestinalis	C		●	●	●				●	●	●	●
Porphyra sp.	R		●						●		●	●
8 Scytosiphon	P		●	●			●	●	●	●		
Porphyra miniata	R		●					●	●			
Enteromorpha linza	C		●	●					●	●	●	
9 Ulva lactuca	C		●	●	●		●		●	●	●	
Gigartina papillata	R		●	●	●		●	●	●	●	●	
Balanus glandula	I		●	●	●	●	●	●	●	●	●	●
Balanus cariosus	I		●	●	●		●	●	●	●	●	●
Ulva fenestrata	C		●	●	●		●	●	●	●		
Mytilus	II		●		●	●	●	●	●	●		
10 Pterosiphonia bipinnata	R		●	●	●		●	●	●			
Polysiphonia sp.	R		●		●	●	●	●	●			
Anthopleura	III		●		●		●	●	●	●		
Ralfsia	P		●	●	●		●	●	●	●		
Hildenbrandia	R		●		●		●		●	●		●
Fucus	P		●	●	●		●	●	●	●	●	
Bacillariophycophyta	D		●	●	●	●	●	●	●	●		
Cryptosiphonia	R		●	●	●			●	●			
Rhodomela	R				●			●	●			
Odonthalia floccosa	R		●	●	●			●				

The most abundant red algae reported by Harlin (1969) were Iridaea cordata and Gigartina exasperata, and the predominant brown algae was Laminaria saccharina which formed a continuous belt around Steamboat Island. All of these species have been reported for the Main Basin (Table VI-1).

In all areas spatial differences in benthic flora may be affected by biological factors (predation, competition for space). Biological factors (herbivory) exert a major controlling effect on benthic algae in the San Juan Islands (Mumford, 1973). Sea urchin grazing on one kelp (Laminaria) led to the dominance of another (Agarum). Mumford (1973) indicated that limpets can have a profound effect on percent cover by eating macroalgal germlings that may be similar in size to a diatom.

BENTHIC INVERTEBRATE FAUNA

Species Assemblages

Benthic invertebrate fauna have generally been categorized by three criteria: 1) where the organism usually lives in relation to the sediment surface (e.g., infauna and epifauna); 2) at what depth it is predominantly found (e.g., intertidal or subtidal); 3) and by size, as dictated by sampling and/or sieving techniques (e.g., macrofauna and meiofauna). There are no absolute rules for differentiating all organisms into these categories. Puget Sound researchers have not always used the same sampling and sieving techniques, making quantitative comparisons among studies difficult. However, general reference to the depth and size categories will be made within this section. From a size viewpoint, "macrofauna" will refer to organisms retained on a 1 mm screen after sieving, "meiofauna" to organisms retained on a 0.1 mm screen after seiving, and "microfauna" to organisms passed through a 0.1 mm screen. Wherever possible, reference will be made in presenting data as to sampling procedure.

The benthic invertebrate fauna assemblage of Puget Sound is diverse; Lie (1974) reported greater than 157 species and Nichols (1970) reported about 135 species for predominantly subtidal sampling sites. Armstrong (1977) reported 302 species and Houghton (1973) reported greater than 242 species for predominantly intertidal sampling sites within Puget Sound. Simenstad et al. (1980) reported approximately 235 taxa of invertebrate epifauna for sampling conducted along the southern shore of the Strait of Juan de Fuca.

Intertidal Fauna. The benthic invertebrate fauna assemblages are somewhat unique between intertidal and subtidal habitats. Although some species are found in both habitats, this discussion will separately discuss benthic invertebrate assemblages as intertidal or subtidal. The benthic invertebrate fauna listed in Table VI-4 represent common intertidal species found in the Main Basin. It was condensed from the most complete intertidal species list in the study area (Armstrong, 1977). Nine invertebrate phyla are represented with the most abundant species found in the mollusca, annelida, and arthropods. The class polychaeta (Annelida) have the greater number of species. Molluscs and crustaceans (Arthropods) have about 80 percent as many species as the polychaetes. There are, however, more species for particular taxa (e.g., Nematoda, Oligochaeta) which are typically not speciated due to identification difficulties. As shown (Table VI-4) habitats of these species varied from +6 feet to -2 feet from MLLW. Substrate varied from sand to boulders.

Subtidal Fauna. Benthic invertebrate fauna typically found in subtidal habitats throughout Puget Sound are listed in Table VI-5. These data, primarily from Lie (1974), show the dominance in abundance and number of species of crustacea (especially amphipods) and mollusca in subtidal areas. Although not included in Lie (1974), the common polychaetes sampled by Lie (1968) for the Main Basin are also listed.

The relative contributions of several of the major subtidal taxa to the total biomass are shown in Figure VI-6. The total mean biomass for 48 stations sampled was about 13.8 g/m^2 (dry weight). Molluscs and polychaetes contributed about 35 and 25 percent of this biomass, respectively.

Life Cycles

The information on life cycles of individual benthic macrofauna species of Puget Sound is extremely limited. Table VI-6 summarizes life history information for several organisms with commercial or recreational value. Life cycle information for most of the abundant organisms listed in previous tables was not located in this review.

Thorson (1957) states that about two-thirds of the benthic fauna in the cold temperate seas have pelagic larvae. This trend is supported by data in Table VI-6. Eggs and larvae number in the thousands to millions per spawning invertebrate. In general the pelagic larvae of polychaetes, molluscs, and echinoderms exist in this life stage for about three weeks. During this time, the larvae respond to various stimuli including light intensity, substrate, salinity, temperature, and density (stratification). Hatched larvae are photopositive and rise to the surface

TABLE VI-4

COMMON INTERTIDAL BENTHIC INVERTEBATE MACROFAUNA RECORDED AT MAIN BASIN BEACHES BY[1]
ARMSTRONG (1977)

Taxa	Total Number of Species Recorded For Taxonomic Level	Habitat[2]
PHYLUM PORIFERA	2	
Haliclona permollis (Bowerbank)		0; Bo,Co
Halichondria panacea (Pallas)		0; Bo,Co
PHYLUM CNIDARIA	8	
Anthopleura artemisia (Pickering)		0,+3; Bo,Co
Anthopleura elegantissima (Brandt)		0,+3; MSi,Si
Haliplanella luciae (Verrill)		0,+3,+6; Co
Metridium senile (Linnaeus)		0; Bo
Ptilosarcus gurneyi (Gray)		-2; Si
PHYLUM PLATYHELMINTHES	>1	
Order POLYCLADIDA		0,+3; Co,Cu
PHYLUM NEMERTEA	6	
Amphiporus formidabilis Griffin		0; Bo
Emplectonema gracile (Johnston)		0,+3; MSo, Bo,Co
Paranemertes peregrina Coe		0,+3; MSo,Bo,Co
PHYLUM NEMATODA	>1	0,+3,+6; MSi,Si
PHYLUM MOLLUSCA	64	
Class AMPHINEURA	7	
Cyanoplax dentiens (Gould)		0,+3,+6; Bo,Co
Katharina tunicata (Wood)		0; Bo,Co
Mopalia ciliata (Sowerby)		0;+3+; Bo,Co
Mopalia lignosa (Gould)		0,+3; Bo,Co
Mopalia muscosa (Gould)		0,+3; Bo,Co
Tonicella lineata (Wood)		0; Bo,Co
Class BIVALVIA	27	
Clinocardium nuttallii (Conrad)		0,+3; MSi,Si
Macoma balthica (Linnaeus)		0,+3,+6; MSi,Si
Macoma inquinata (Deshayes)		0,+3,+6; MSi
Macoma incongrua (Martens)		0,+3; MSi
Macoma nasuta (Conrad)		0,+3; MSi,Si
Tellina modesta (Carpenter)		0; Si
Mytilus edulis Linnaeus		0,+3,+6; Bo,Co
Mya arenaria Linnaeus		0,+3,+6; MSi
Hiatella arctica (Linnaeus)		0; Bo,Co
Tresus capax (Gould)		0,+3; MSi
Protothaca staminea (Conrad)		0,+3; MSi
Saxidomus giganteus Dehayes		0,+3; MSi
Transennella tantilla (Gould)		0,+3; MSi
Tapes japonica Deshayes		+6; MSi
Mysella ? tumida (Carpenter)		0,+3; MSi
Pododesmus cepio (Gray)		0; Bo
Zirfaea pilsbryi Lowe		0,+3; Ri
Bankia setacea Tyron		+3; in wood
Class GASTROPODA	29	
Subclass PROSOBRANCHIA	15	
Collisella digitalis (Rathke)		+6; Bo
Collisella pelta (Rathke)		+3,+6; Bo,Co
Collisella strigatella (Carpenter)		0,+3,+6; Bo,Co
Notoacmea persona (Rathke)		+3,+6; Bo,Co
Notoacmea scutum (Rathke)		0,+3; Bo,Co
Lacuna ? variegata (Carpenter)		0,+3; Ao,Co
Littorina scultulata Gould		+3,+6; Co
Littorina sitkana Philippi		+3,+6; Co
Nassarius mendicus (Gould)		0; Ao,Co,MSo
Thais emarginata (Deshayes)		0,+3; Bo,Co
Thais lamellosa (Gmelin)		0,+3; Bo,Co

TABLE VI-4 (CONTINUED)

Subclass OPISTHOBRANCHIA	14	
Onchidella borealis Dall		+3,+6; Bo,Co
Onchidoris bilamellata (Linnaeus)		0; Co,Cu
Hermaea vancouverensis (O'Donoghue)		0; Ao
		(Spongomorpha sp.)
Stiliger fuscovittata Lance		0; Ao
		(Pterosiphonia bipinnata)
Class CEPHALOPODA	1	
PHYLUM SIPUNCULA	1	
PHYLUM ANNELIDA	>99	
Class POLYCHAETA	97	
Ampharetidae	1	
Arenicolidae	2	
Branchiomaldane vincentii Langerhans		+3,+6; MSi
Capitellidae	5	
Capitella capitata (Fabricius)		0,+3; MSi
Medimastus capensis Day		0,+3,+6; MSi
Notomastus lineatus Claparede		0,+3,+6; MSi
Notomastus tenuis Moore		0,+3.+6; MSi
Chaetopteridae	1	
Spiochaetopterus costarum (Claparede)		0; Si,Ti
Chrysopetalidae	1	
Paleanotus bellis (Johnson)		0; MSi
Cirratulidae	6	
Cirratulus cirratus (Muller)		0,+3; MSi,Si
Dorvilleidae	3	
Undescribed dorvilleid		0,+3,+6; MSi
Protodorvillea gracilis (Hartman)		0,+3,+6; MSi
Glyceridae	3	
Glycera americana Leidy		0,+3; MSi
Glycera capitata Oersted		0,+3; MSi
Hemipodus borealis Johnson		0,+3,+6; MSi
Goniadidae	1	
Glycinde picta Berkeley		0,+3; MSi
Hesionidae	2	
Micropodarke dubia (Hessle)		0,+3; MSi
Lumbrineridae	1	
Lumbrineris zonata (Johnson)		0,+3,+6; MSi
Magelonidae	3	
Maldanidae	1	
Nephtyidae	5	
Nephtys caeca (Fabricius)		0,+3; MSi,Si
Nephtys caecoides Hartman		0,+3; MSi,Si
Nereidae	7	
Nereis procera Ehlers		0,+3; MSi
Nereis vexillosa Grube		+3,+6; MSi
Nereis zonata Malmgren		0,+3,+6; MSi
Platynereis bicanaliculata (Baird)		0,+3; Co,Ti

TABLE VI-4 (CONTINUED)

Opheliidae	2	
Armandia brevis (Moore)		0,+3; MSi,Si
Ophelia limacina (Rathke)		0,+3; Si
Onuphidae	2	
Onuphis elegans (Johnson)		0; Si,Ti
Orbinidae	4	
Scoloplos armiger (Muller)		0,+3; Si
Scoloplos pugettensis Pettibone		0,+3, Si
Oweniidae	1	
Owenia fusiformis delle Chiaje		0,+3; MSi,Ti
Paraonidae	1	
Paraonella platybranchia (Hartman)		+3,+6, Si
Parergodrilidae	1	
Pectinaridae	1	
Pectinaria granulata Linnaeus		0; MSi,Ti
Phyllodocidae	4	
Eteone longa (Fabricius)		0,+3; MSi
Eulalia quadrioculata (Moore)		0,+3; MSi
Phyllodoce maculata (Linnaeus)		0,+3; MSi,Si
Pilargidae	3	
Sigambra tentaculata (Treadwell)		0,+3; MSi
Pisionidae	1	
Polynoidae	7	
Arctonoe fragilis (Baird)		0, COM Evasterias troschelii
Polyeunoa tuta (Grube)		0; COM Neoamphritrite robusta
Serpulidae	1	
Serpula vermicularis Linnaeus		0, Bo
Sabellidae	5	
Eudistylia ? polymorpha (Johnson)		0; Bo
Eudistylia vancouveri (Kinberg)		0; Bo
Pseudopotamilla occelata (Moore)		0; Bo
Schizobranchia insignis Bush		0; Bo
Sigalionidae	1	
Pholoe minuta (Fabricius)		0,+3; MSi
Spionidae	11	
Malacoceros glutaeus (Ehlers)		0,+3,+6; MSi
Polydora columbiana (Berkeley)		0,+3,+6; MSi
Polydora natrix (Soderstrom)		0,+3,+6; MSi
Prionospio cirrifera Wiren		0,+3; MSi
Prionospio steenstrupi Malmgren		0,+3; MSi
Pygospio elegans Claparede		0,+3,+6; MSi
Scolelepis foliosa (Audouin & Milne-Edwards)		0,+3, MSi
Spio filicornis (Muller)		0,+3, MSi
Spiophanes bombyx (Claparede)		0,+3, Si,Ti
Syllidae	7	
Syllides longocirrata Oersted		0,+3, Si
Syllis adamantea adamantea (Treadwell)		+3,+6, MSi
Syllis alternata Moore		0,+3,+6, MSi
Syllis heterochaeta Moore		0,+3; MSi
Syllis pulchra Berkeley & Berkeley		0,+3; MSi
Terebellidae	2	
Neoamphitrite robusta (Johnson)		0; Bo,Co,Ti

TABLE VI-4 (CONTINUED)

Protodrilidae	1	
Protodrilus flabelliger Wieser		+3,+6; Si
Saccocirridae	1	
Saccocirrus eroticus Gray		0,+3,+6; Si
Class OLIGOCHAETA	>1	0,+3,+6; Msi,Si
Class HIRUDINEA	>1	+6; Ao
PHYLUM ARTHROPODA	>70	
Class ARACHINIDA	1	
? _Lohmannella_ sp.		+6; Ao,Bo,Co
Class INSECTA	>2	
Order DIPTERA	>1	+3,+6; Ao,Bo,Co
Order COLEOPTERA	>1	+3,+6; Ao,Bo,Co
Class CRUSTACEA		
Subclass CIRRIPEDIA	4	
Balanus glandula Darwin		0,+3,+6; Bo,Co
Balanus cariosus (Pallas)		0,+3; Bo,Co
Balanus crenatus Bruguiere		0,+3; Bo,Co
Chthamalus dalli Pilsbry		+6; Bo,co
Order TANAIDACEA	1	
Leptochelia dubia (Kroyer)		0,+3; Si,MSi,Ti
Order ISOPODA	11	
Excirolana kincaidi (Hatch)		+6; Si
Dynamenella sheareri (Hatch)		0,+3; Bo
Exosphaeroma media George & Stromberg		0,+3,+6; Ao,Bo,Co, MSi,MSo,Si,So
Exosphaeroma ? octoncum Richardson		0,+3; Ao,Co,MSo
Gnorimosphaeroma oregonensis (Dana)		0,+3,+6;; Ao,Bo,Co, MSi,MSo,Si,So
Idotea wosnesenkii (Brandt)		0,+3; Bo,Co,MSo
Ligia pallasii Brandt		+10; Bo
Order LEPTOSTRACA	1	
Order AMPHIPODA	37	
Suborder GAMMARIDEA	34	
Ampithoidae	3	
Ampithoe simulans Alderman		0,+3; Ao,Co,MSo
Aoridae	1	
Aoroides columbiae Walker		0; Ao,MSo
Atylidae	1	
Calliopiidae	2	
Calliopiella pratti Barnard		0,+3; Ao,MSo
Calliopius undescribed sp. 1		0,+3; Ao,So
Corophiidae	2	
Corophium acherusicum Costa		0,+3,+6; Ao,Si, MSi,Ti
Corophium brevis Shoemaker		0,+3; MSi,Ti
Calliopiellidae	1	
Oligochinus lighti Barnard		+3; MSo

TABLE VI-4 (CONTINUED)

Eusiridae	4	
Paramoera undescribed sp. 1		+3,+6; MSo
Pontogeneia cf.ivanovi Gurjanova		0,+3, Ao,MSo
Gammaridae	3	
Anisogammarus confervicolus (Stimpson)		+3,+6, Ao,MSo,So
Anisogammarus pugettensis (Dana)		0,+3; Ao,MSo
Haustoriidae	1	
Eohaustorius washingtonianus (Thorsteinson)		0; Si
Isaeidae	1	
Photis brevipes Shoemaker		0,+3; Ao,MSi,Si,Ti
Ischyroceridae	2	
Lysianassidae	1	
Oedicerotidae	3	
Synchelidium shoemakeri Mills		0,+3; Ao,MSi
Phoxocephalidae	3	
Pleustidae	1	
Superfamily Talitroidea	7	
Allorchestes angustus Dana		0,+3,+6; Ao,Co, MSi,MSo
Hyale frequens (Stout)		0,+3; Ao,Co,MSo
Hyale plumulosa (Stimpson)		+6; MSo
Hyale grandicornis californica (Barnard)		+8; Bo
Orchestoidea pugettensis (Dana)		+6; MSi,MSo,Si,So
Suborder CAPRELLIDEA	3	
Caprella laeviuscula Mayer		0,+3; Ao,MSo
Order CUMACEA	3	
Cumella vulgaris Hart		0,+3,+6; Ao,MSi, MSo,Si,So
Diastylopsis dawsoni Smith		0; MSi,Si
Lamprops quadriplicata Smith		0,+3, MSi,Si
Order DECAPODA	27	
Suborder NATANTIA	6	
Section CARIDEA	6	
Crangon nigricauda Stimpson		0; MSi,Si
Heptacarpus sitchensis (Brandt)		+6; TPi
Pandalus danae Stimpson		0, TPi
Suborder REPTANTIA	21	
Section BRACHYURA	13	
Hemigrapsus oregonensis (Dana)		0,+3,+6, Cu
Cancer oregonensis (Dana)		0,+3, Bo
Cancer productus Randall		0,+3, Cu,MSi
Lophopanopeus bellus (Stimpson)		0, Cu
Pugettia gracilis Dana		0; Co,Cu
Pugettia producta Randall		0; Co,Cu
Pinnixa faba (Dana)		0,+3; COM in bivalve molluscs
Pinnixa schmitti Rathbun		0,+3,COM in bivalve molluscs

TABLE VI-4 (CONTINUED)

Section ASTACURA	2	
Callianassa ? gigas Dana		0; MSi
Upogebia pugettensis (Dana)		0,+3; MSi
Section ANOMURA		
Pagurus hirsutiusculus (Dana)		0,+3,+6; Co,MSo
Pertrolisthes eriomerus Stimpson		0; Cu
PHYLUM BRYOZOA	>1	
PHYLUM PHORONIDEA	1	
Phoronopsis harmeri Pixell		
PHYLUM ECHINODERMATA	14	
Class ASTEROIDEA	7	
Evasterias troschelii (Stimpson)		0; Co
Class ECHINOIDEA	2	
Class HOLOTHUROIDEA	4	
Cucumaria miniata (Brandt)		0; Bu
Eupentacta quinquesemita (Selenka)		0; Bu
Leptosynapta clarki Heding		0,+3; MSi
Class OPIUROIDEA	1	
Amphiodia occidentalis (Lyman)		0; Cu

FOOTNOTES TO TABLE VI-4:

(1) Condensed from Armstrong (1977) to list only those predominantly intertidal species with greater than or equal to 2 per m^2 during any one season throughout the year. The five Main Basin beaches sampled were Richmond Beach, Careek Park, West Point, Alki Point, and Lincoln Park.

(2) Tide heights are given in feet above or below MLLW. Mixed-sediments are a mixture of sands and gravel up to about 60 mm in diameter. Cobble are large rocks from approximately 60 mm to 250 mm in diameter. Boulders are rocks larger than cobble.

Ao = on algae, Bo = on boulders, Bu = under boulders, Co = on cobble, Cu = under cobble, MSo = on mixed-sediments, MSi = in mixed-sediments, Ri = in rock, So = on sand, Si = in sand, Ti = in tubes, TPi = in tide pools, COM = commensal with, PAR = parasitic on.

(3) Depth Range = +6 to -2 from MLLW, Sample Size = 0.25 m^2 quadrat to 25 cm deep; and 31.2 cm^2 cored subsample to 15cm deep, Sieve Size = Epifauna = 1 mm mesh, Infauna = 6 and 1 millimeter mesh.

while older larvae, ready to metamorphize, are photonegative and begin settlement. Pygospio elegans, Balanus balanoides, Mytilus edulis and other nearshore organisms found in shallow intertidal habitats have a positive phototaxis when near settlement, allowing for surface crowding and shallow, intertidal settlement (Thorson, 1957). Physical effects such as stratification may play an important role in which substrate the larvae may settle upon. Species may be restricted in particular salinity or temperature strata and may never have a chance to come into contact with all substrate types. An example, cited by Thorson (1957), is Pygospio elegans which is resistant to brackish water and photopositive, thus it tends to be located in surface waters and kept away from deep mud areas.

It is still speculative as to what principally influences the location of benthic larval settlement. Thorson (1957) states that it is probable that planktonic larvae respond positively to the appropriate substrate. However, Clements and Shelford (1946) regarded the hydrographic conditions listed above as more essential to bottom fauna than substrate composition in Puget Sound near San Juan Island.

Temporal Changes

Temporal changes in intertidal benthic communities have been documented outside the study area by Nyblade (1977 and 1978), Smith and Webber (1978), and Webber (1979) within the San Juan Islands, the Strait of Juan De Fuca, the northwest shore of Whidbey Island and the Northern Puget Sound area. Within the study area Armstrong (1977), Feller (1977), and Staude et al. (1977) described the temporal changes in abundance of intertidal fauna in the Main Basin.

Figure VI-7 compares the seasonal changes in abundance and biomass of benthos for three sites on Whidbey Island. Intertidal and shallow subtidal areas (combined) show a general trend toward higher abundances and biomasses during the summer and/or fall seasons. Figure VI-8 shows the high variability encountered in temporal measurements of an intertidal population of harpacticoid copepods in the Main Basin. This variability, although not shown in Figure VI-7, is common in Puget Sound data reviewed for this report. Webber (1979) cautioned that seasonal changes are much more complex than the general pattern shown in Figure VI-7, and, therefore, should be examined on an individual species basis.

A summary of seasonal observations for intertidal taxa of the Main Basin is shown in Table VI-7. These data show that polychaetes, molluscs, and crustaceans were either bearing or depositing eggs and existing as juveniles during all seasons in the Main Basin. Egg observations peaked in October for polychaetes while molluscs and crustaceans peaked in April. A summary of spawning times and larval presence for individual organisms having planktonic larvae is presented in Table VI-8.

TABLE VI-5

COMMON SUBTIDAL INVERTEBRATE MACROFAUNA
OF PUGET SOUND - LIE (1968, 1974)[1]

PHYLUM ARTHROPODA

   Class Crustacea[3]
     Heterophoxus oculatus (Holmes)[4]
     Pinnixa schmitti Rathbun[5]
     Ampelisca macrocephala Lilljeborg
     Euphilomedes charcharodonta (V.Z. Smith)[5,6]
     Eudorella pacifica Hart[5]
     Euphilomedes producta Poulsen
     Byblis veleronis Barnard
     Westwoodilla caecula (Bate)
     Pinnixa occidentalis Rathbun
     Cyphocaris challengeri Stebbing
     Paraphoxus variatus Barnard[6]
     Leptochelia dubia Kroyer[6]
     Lophopanopeus bellus (Stimpson)[6]

PHYLUM MOLLUSCA

   Class Bivalvia[7]
     Mysella tumida (Carpenter)[8]
     Axinopsida serricata Carpenter[2,9,10,12]
     Macoma carlottensis (Whiteaves)[8,9,10,12]
     Nucula bellotii Adams[8]
     Pandora filosa (Carpenter)[8]
     Parvalucina tenuisculpta (Carpenter)[8]
     Psephidia lordi Baird
     Acila castrensis (Hinds)
     Crenella columbiana Dall
     Compsomyax subdiaphana (Carpenter)
     Lucinoma annulata (Reeve)
     Mya arenaria Linne
     Lyonsia pugethensis Dall
     Macoma incongrua (vonMartens)
     Macoma elimata
     Macoma alaskana Dall
     Macoma calcarea Gmelin[11]
     Semele rubropicta Dall[11]

PHYLUM ECHINODERMATA[13]

   Class Holothuroidea
     Leptosynapta clarki Heding

   Class Ophiuroidea
     Amphoidia urtica (Lyman)[14]
     Ophiura lutkeni (Lyman)
     Amphipholis squamata (Delle Chiaje)

   Class Echinoidea
     Briaster townsendi Agassiz[11]

PHYLUM ANNELIDA

   Class Polychaeta
    Subclass Errantia
     Glyceridae
       Glycera americana Leidy
       Glycera capitata Oersted

     Goniadidae
       Goniada brunnea Treadwell

     Lumbrineridae
       Lumbrineris luti Berkeley and Berkeley
       Lumbrineris californiensis Hartman
       Lumbrineris cruzensis Hartman
       Lumbrineris bicirrata Treadwell

PHYLUM ANNELIDA continued

     Nephtyidae
       Nephtys ferruginea Hartman

     Nereidae
       Platynereis bicanaliculata (Baird)

     Onuphidae
       Onuphis iridescens (Johnson)

     Maldanidae
       Euclymeninae (Several species)
       Euclymene zonalis (Verrill)
       Nicomache lumbricalis (Fabricius)
       Praxilella affinis pacifica Berkeley
       Praxilella gracilis (Sars)

     Opheliidae
       Armandia brevis (Moore)
       Travisia pupa Moore

     Orbiniidae
       Haploscoloplos pugettensis (Pettibone)

     Cossuridae
       Cossuridae sp.

     Paraonidae
       Paraonella spinifera
       Aricidea cf. lopezi

     Pectinariidae
       Pectinaria californiensis Hartman
       Pectinaria granulata (Linne)

     Spionidae
       Laonice cirrata (Sars)
       Prionospio cirrifera Wiren
       Prionospio malmgreni Claparede
       Prionospio pinnata Ehlers

     Polynoidae
       Harmothoe imbricata (Linne)
       Lepidasthenia berkeleyeae Pettibone
       Malmgrenia lunulata (Delle Chiaje)
       Peisidice aspera Johnson

     Sigalionidae
       Pholoe minuta (Fabricius)

     Syllidae
       Pionosyllis uraga Imajima

     Pilargidae
       Sigambra tentaculata (Treadwell)

    Subclass Sedentaria
     Capitellidae
       Several Species

     Cirratulidae
       Chaetozone setosa Malmgren
       Caulleriella alata (Southern)

TABLE VI-5 (Continued)

FOOTNOTES

(1) Includes all crustaceans, bivalves and echinoderms for stations
     throughout Puget Sound in February/March, 1969. Polychaetes and
     other groups not identified by Lie (1974). Polychaetes listed
     from Lie (1968) for Main Basin transect sampled quarterly in 1963.
     Generally represents species which contributed about 70 percent to
     total abundance at any separate sampling station.

(2) Depth Range 9 to 260 m for organisms from Lie (1974).
     Depth range from 9 to 216 m for polychaetes from Lie (1968).
     Sample size was 0.1 m^2 Van Veen grab; sieve size was 1 mm.

(3) All organisms listed; abundance > 6.5 organisms per m^2 and
     percent occurrence > 16 percent of samples.

(4) Frequently occurring; percent occurrence = 35 percent of samples.

(5) Numerically abundant; abundance > 181.5 organisms per m^2.

(6) Most abundant infauna species in Puget Sound according to Lie
     (1968).

(7) All organisms listed; abundance > 3.5 organisms per m^2 and
     percent occurrence 13 percent samples.

(8) Frequently occurring; percent occurrence > 30 percent of samples.

(9) Numerically abundant; abundance > 198 organisms per m^2.

(10) Ranked in the 15 most common taxa for Elliott Bay by abundance,
     percent occurrence, biomass, D.E. Anderson, URS Company (1981),
     personal communication.

(11) Not listed in Lie (1974), but listed in Lie (1968).

(12) Appears to be restricted to stations in Main Basin, nearly
     non-existent in southern Puget Sound.

(13) All organisms listed; abundance > 23.5 organisms per m^2 and
     percent occurrence > 15 percent of samples.

(14) Numerically abundant; abundance > 243.5 organisms per m^2
     and frequently occurring; percent occurrence = 28 percent of
     samples.

SAMPLING INFORMATION
● Sample Station
Depth Range   9-163m
Sample Size   0.2m² VanVeen
Sieve Size   1mm mesh

MEAN TOTAL BIOMASS (g/m², DRY WEIGHT)*

0	5	10	15
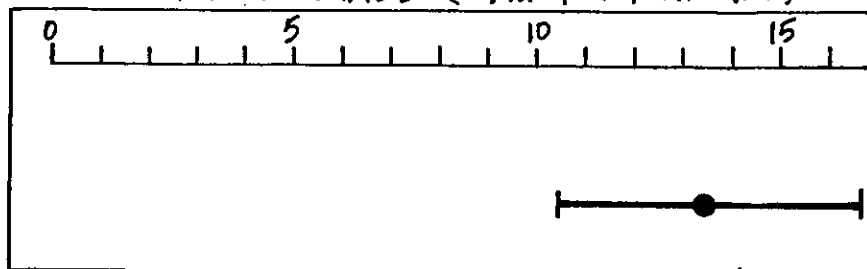
PERCENT CONTRIBUTION TO MEAN TOTAL BIOMASS

0	10	20	30	40	50
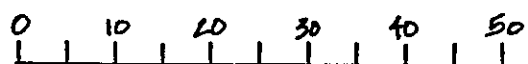
MOLLUSCA

POLYCHAETA

ECHINODERMATA

OTHER GROUPS

CRUSTACEA

*BRACKETS REPRESENT 95% CONFIDENCE INTERVAL

Figure VI-6. Mean Standing Crop and Percent Contribution by Major Subtidal
      Invertebrate Macrofaunal Taxa in Puget Sound, February and March
      1969.

Source: Lie, 1974.

TABLE VI-6

LIFE CYCLE INFORMATION ON SELECTED BENTHIC INVERTEBRATES
Grassle and Grassle (1974)

Organism	Eggs & Larvae(1) Type	Sex(2)	Spawning(3) Season	Number Of Broods Per Season	Number Of Eggs/(4) Larvae	For(5) Larval Maturation	Sexually(6) Mature Adult	Reference
Polychaeta								
Capitella capitata	P	Di	1°S, TY	>1	6->600E	30-60D		Grassle&Grassle (1974)
Polydora ligni	P		TY	>2		42D		"
Nereis succinea	P		S			1,000,000E		"
Mollusca								
Panope generosa (geoduck)	P	Di	Sp,S	1				Goodwin (1973)
Crassostrea gigas (Pacific Oyster)	P	Mo	S		50-100M	18-30D	1y	Cheney (In Press)
Ostrea lurida (Olympia Oyster)	F	Mo	Sp,1°S,F		250-300T,L	> 30D	2y	"
Saxidomus giganteus (butter clam)	P	Di	Sp,S		T,HT	21D	1y	"
Protothaca staminea (native littleneck)	P	Di	1°Sp,S		T,HT	21D	1y	"
Venerupsis japonica (Manila or Japanese littleneck)	P	Di	Sp,1°S,F		T,HT	21D	1y	"
Tresus nuttalli (horse clam)	P	Di	S		T,HT	21D	3y	"
T. capax (horse clam)	P	Di	W,Sp		T,HT	21D	3y	"
Clinocardium nuttalli (cockle)	P	Di	Sp,S		T,HT	21D	2y	"
Scallops(7)	P	Di	S,F		0.10-150 per liter,L	14D	4.5y	"
Mytilus edulis (bay mussel)	P	Di	Sp,S			21-28D	1y	"
Mytilus californianus (sea mussel)	P	Di	1°S,W			21-28D	1Y	"
Octopus dofleini (octopus)	B	Di	Sp,S	1		W-Mn	1.5-2y	"
Crustacea								
Cancer magister (Dungeness crab)	B	Di	TY		Up to 1.5M	3-5Mn		"
Echinodermata								
Stichopus californicus (sea cucumber)	P	Di	S		Up to 3M	15-23D		"
Strongylocentrotus franciscanus (red sea urchin)	P	Di	Sp-S		Up to 2M	2-3Mn		"

(1) P= eggs & larvae planktonic; B= eggs brooded, larvae planktonic
(2) Di= sexes usually separate (dioecious); Mo=both sexes in single organism (monoecious)
(3) 1°= primarily; S= Summer; TY= Throughout year; Sp= Spring; F= Fall; W= Winter
(4) E= eggs; L= larvae; M= million; T= thousand; HT= hundred thousands
(5) D= Days, Mn= Months, W= Weeks
(6) Y= Years
(7) Includes common Puget Sound scallops= Pecten caurinus (weather vane scallop), Chlamys hastata and C. rubida (pink scallop), and Hinnites multirugosus

Lie and Evans (1973) evaluated the long-term variability in the structure of deep subtidal benthic communities by comparing data from 1963-1964 to 1967 and 1969. Specific data characterizing the temporal changes included the total number of species, abundance, biomass, and species composition of benthic infauna in the Main Basin. There was no significant seasonal trend in the total number of species; however, there was considerable seasonal variability in abundance. Summer maximum abundances were about 90 percent higher than winter minimum abundances. On an annual mean basis, the abundances were similar, suggesting overall stability. Lie (1974) states that subtidal benthic infauna biomass does not vary extensively seasonally or annually in Puget Sound. Nichols (personal communication) has observed longer term (i.e., 2-3 year), cyclical trends in populations of subtidal benthos in the Main Basin. Harman and Serwold (1977) monitored a subtidal dredged material disposal site in Elliott Bay over a 9-month sampling period. Figure VI-9 shows the seasonal change in abundance and biomass for Elliott Bay subtidal benthic macrofauna (data from Harman and Serwold, 1977). Similar to observations by Lie and Evans (1973), abundances revealed summer maxima. Biomass, in contrast to Lie's (1974) observations, also peaked in the summer and fall. Whether or not these authors' statements are contradictory is uncertain because no statistical treatment of seasonal trends were found.

Environmental parameters (temperature, salinity, oxygen) do not exhibit large seasonal fluctuations in Puget Sound and this may explain why the species composition is diverse for the subtidal benthos of Puget Sound. It is more diverse than sites at other comparable latitudes (Lie and Evans, 1973).

Spatial Changes

Spatial changes in species composition, abundance, and biomass are difficult to document due to varying taxonomic expertise and different sampling techniques used by researchers between studies. Attempts to describe these parameters at different locations in Puget Sound have been both qualitative and quantitative (Armstrong, 1977; Lie, 1974, 1969 and 1968; Nichols, 1968 and 1970; Wennekens, 1959; Clements and Shelford, 1946; Weese and McNab, 1930; and Shelford and Towler, 1925).

Intertidal Fauna - Armstrong (1977) used species classification (cluster) analysis of abundance data (see Boesch, 1977) to define groups of benthic species from the Main Basin. Six groups were defined for each of two different faunal size-classes (Table VI-9). When these groups were compared to the substrate composition of the sampling sites, two general relationships were defined. Group 1, for both size fractions, was associated with fine-grained, wave rippled sand; and the remaining groups (2-4) were associated with cobble-strewn mixed sediments. For the 6 mm size fraction, larger macrofauna were associated with Group 1 while Group 2 contained the most abundant macrofauna.
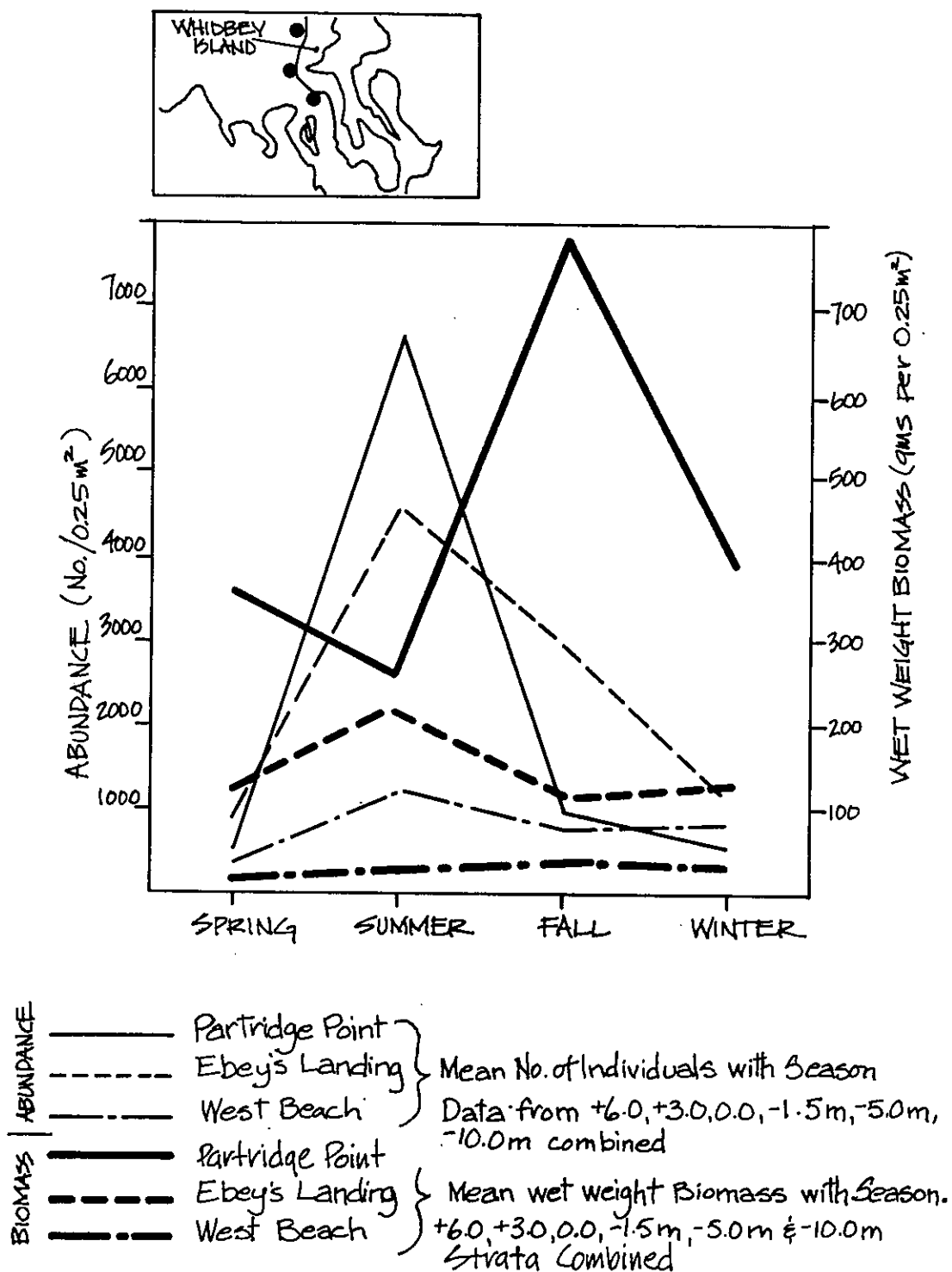
Figure VI-7. Seasonal Changes in Abundance and Biomass of the Intertidal and Shallow Subtidal Benthos off Whidbey Island.

Modified from Webber, 1979.
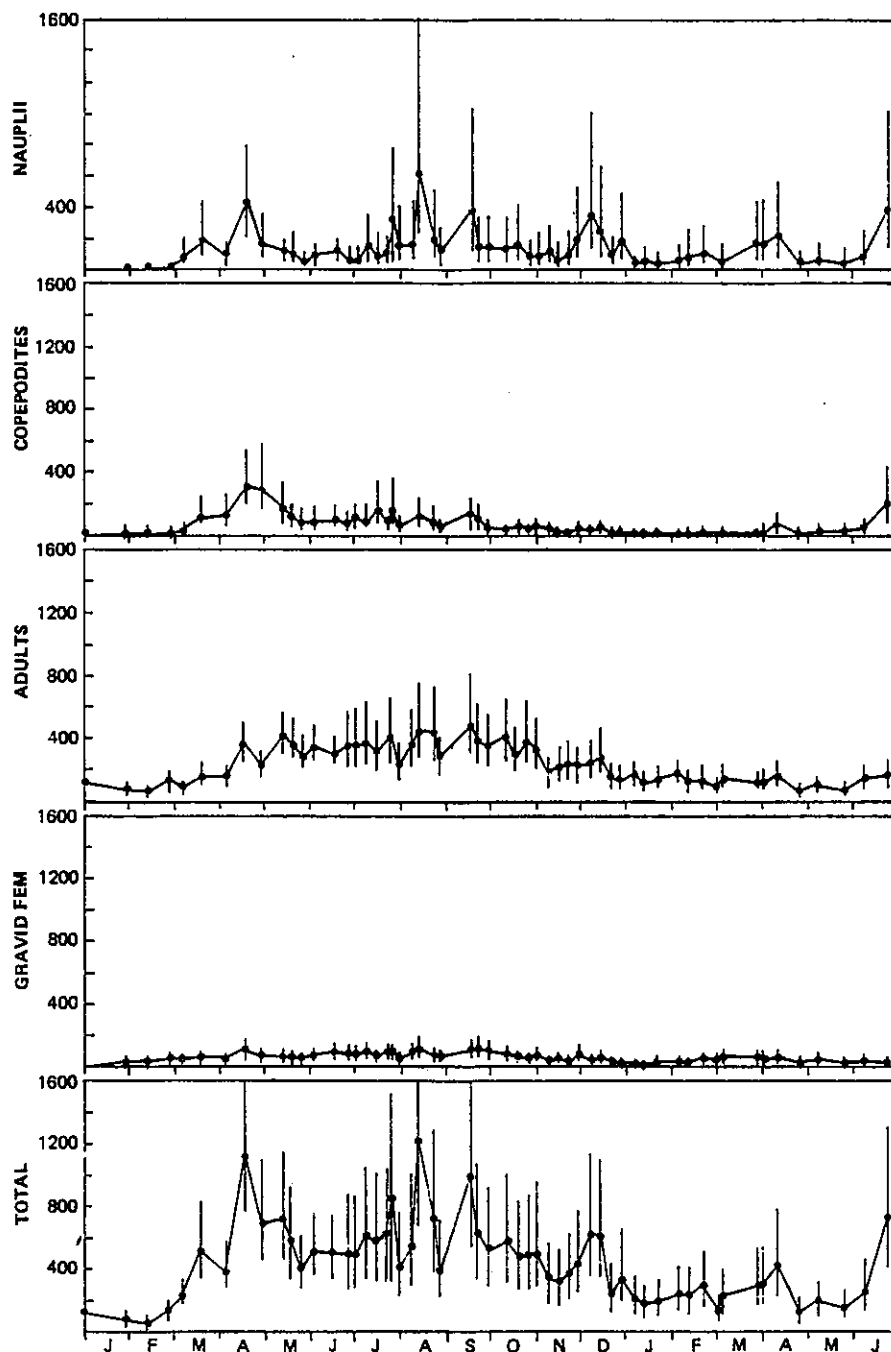
Figure VI-8.   Abundance per 10 cm^2 and 95% Confidence Limits about the Mean for Five Developmental Categories of the Total Harpacticoid Copepod Population in the Upper 5 cm at Station E, Mukilteo.

Source: Feller, 1977.

TABLE VI-7

SEASONAL PERCENTAGE OF THE TOTAL NUMBER OF SPECIES
IN EACH TAXA THAT WERE JUVENILES OR THAT HAD EGGS
(MODIFIED FROM ARMSTRONG, 1977)

TAXA (number of species)	MONTH OF OCCURRENCE			
	January	April	July	October
Nemerteans (2)		$E/^{(1)}100$		
Polychaetes (40)	E/23 $J^{(2)}/15$	E/33 J/25	E/18 J/20	E/65 J/23
Sipunculids (1)		E/100	E/100	E/100
Molluscs (8)	E/38 J/13	E/63 J/25	E/50 J/13	E/25 J/13
Crustaceans (37)	E/27 J/3	E/65 J/11	E/22 J/5	E/38 J/19
Phoronids (1)		E/100		E/100
Echinoderms (2)	E/50 J/50	E/50 J/50	E/50	

(1) E= organisms bearing or depositing eggs.

(2) J= organisms that appeared as juveniles.

TABLE VI-8
SEASONAL PRESENCE OF PLANKTONIC LARVAE
FOR BENTHIC INVERTEBRATES

Organism	J	F	M	A	M	J	J	A	S	O	N	D

Crustacea[b,f]
  Balanus[a,d,h,i,j,k,m]
  Brachymra[a,m]
  Amphipoda[a]

Mollusca[a,f,k,m]
  Bankia[d,h,i,n]
  Mytilus[h,o]
  Crassostrea[p]
  Haliotis[q]

Annelida
  polychaetes[c,f,h,k,l,m]

Echinodermata[f,k]
  Dendraster[e]
  Strongylocentrotus[g]
  Holothurians[e]

Miscellaneous
  Anthopleura (Cnidaria)[e]
  Paranemertea (Nemertea)[r]
  Corella (Urochordata)[h]
  Bryozoa[h,l]

KEY:

▇ Peak Larvae Abundance
☐ Larvae Present

Table VI-8 References:

a Hebard (1956)
b Aron (1958)
*c Johnson (1943)
    Breuer (1940)
    Guberlet (1934)
*d Johnson and Miller (1935)
*e Johnson and Johnson (1950)
*f Bovard and Osterud (1918)
*g Johnson (1932)
h Martin (1938)
i Hower (1938)
*j Thompson and Johnson (1930)

*k Thompson (1936)
*l Chester (1978)
*m Dempster (1938)
n Walden et al. (1967)
*o Johnson (1979); Waterstrat (1979);
     Ahmed and Sparks (1970)
*p Packer (1980)
q Breen and Adkins (1980)
r Roe (1979)

* Hood Canal, North Puget Sound, Strait of Juan de Fuca and
   Strait of Georgia
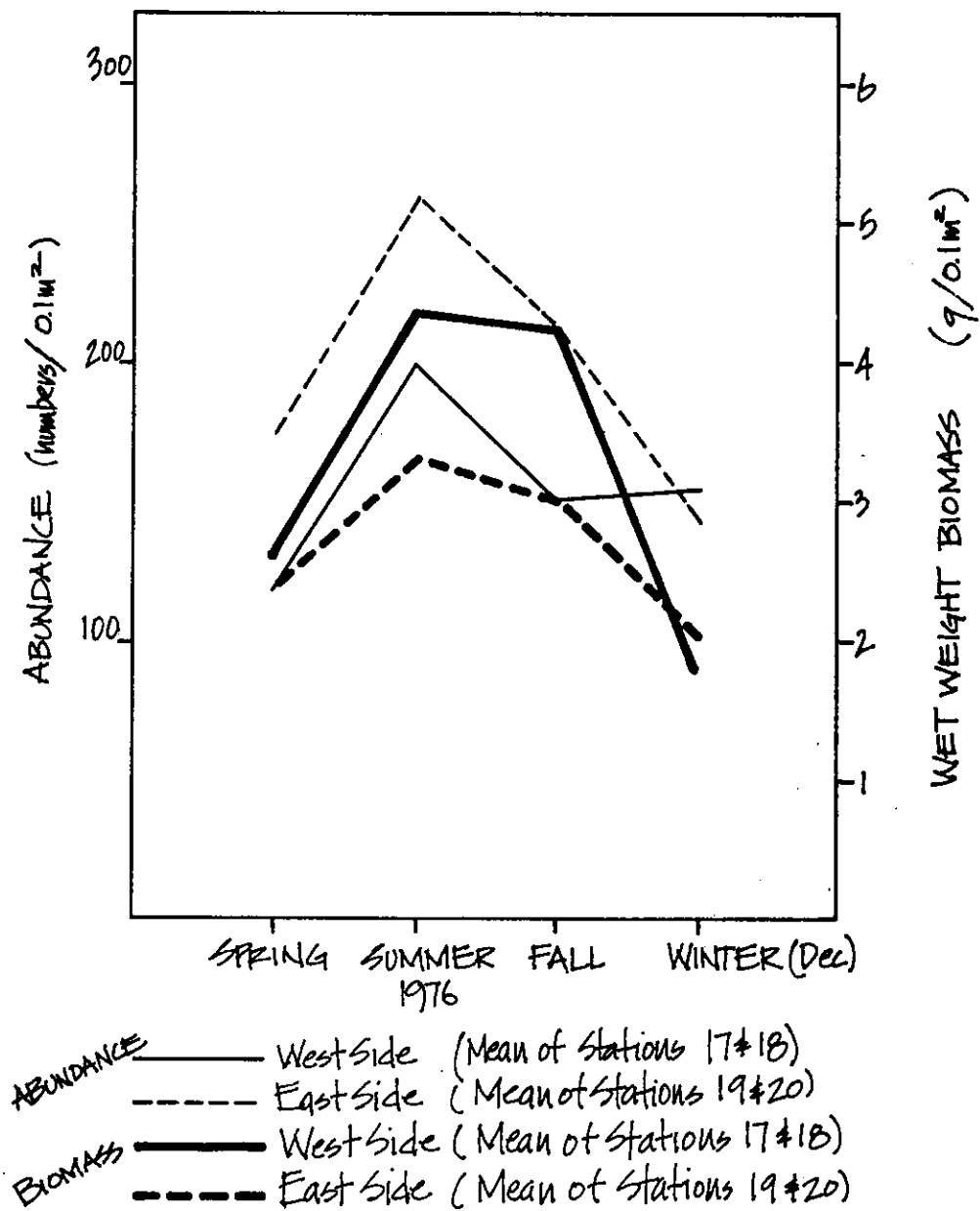
Figure VI-9. Seasonal Changes in Abundance and Biomass of Subtidal Benthos
in Elliott Bay. Reference Stations 17, 18, 19, 20; 3 replicates taken
at each station, depths 47-61 m.

Plotted from data by Harman and Serwold, 1977.

Subtidal Fauna - Changes in species composition, abundance, and biomass for subtidal communities have been documented more extensively than intertidal communities. However, comparisons between studies are difficult for the same reasons as cited above.

Lie (1974) used factor analysis on subtidal macrofaunal abundance data throughout Puget Sound. His analysis resulted in the definition of six groups of species (Figure VI-10). Species composition of these subtidal groups are entirely different from intertidal groups (Armstrong, 1977). Lie (1974) did not include polychaetes; however, none of the other subtidal species (molluscs, crustaceans, or echinoderms) were found in the intertidal groups. Physical parameters such as substrate composition and water depth may help explain why these groups are detectable. Lie (1974) compared the physical parameters of depth and phi-size from these six groups using a Student's "t" test and found some differences did exist (Table VI-10). Group 3 was found at shallower depths than Group 4. Group 1 was located in coarser substrate than Group 2, as was Group 5 to Group 6. The results suggest that these physical parameters may have an influence on structuring the subtidal benthic community. However, the degree to which these parameters influence community structure may be variable between sites. Lie (1974) further analyzed data from 48 stations (Figure VI-11) to define the degree of influence that substrate composition had on community structure and concluded that discrete communities did not exist in Puget Sound. He hypothesized that subtidal benthic infauna in Puget Sound are distributed as a continuum determined by environmental conditions, in particular, sediment texture (mean phi-size) and depth (See Lie, 1974, pp. 211-213). Lie (1974) felt that there was an indication of geographical subdivisions of Puget Sound and that results from experiments in a particular habitat should be applicable to all areas in Puget Sound with similar environmental conditions. Habitats, based on substrate, were defined by Lie as either mud, sand, or gravel. The mud-bottom stations occurred on the mid-channel floor and at the heads of inlets, sand-bottom stations on the slopes and gravel-bottom stations in the narrow passages or near the entrance to the inlets (Figure VI-11). The results of this analysis were in contrast to results of Lie and Kelley (1970) for coastal data which suggested that discrete benthic infauna communities, associated with a particular sediment type, could be identified.

Figure VI-12 shows an analysis of biomass and percent con-tribution by taxa for Lie's 48 stations segregated by sediment type (Figure VI-11). Although confidence intervals demonstrate the wide variability encountered, the mean values suggest that biomass was highest at mud sites. Statistically, however, there was no significant correlation between biomass and depth or between biomass and percent mud. Crustacean biomass tended to be higher progressing from mud to sand to gravel. Mud and sand sites had higher mean biomass of molluscs than gravel sites. Echinoderm biomass was higher at mud sites than at sand and gravel sites.

TABLE VI-9

INTERTIDAL BENTHIC MACROFAUNA SPECIES
GROUPS OF THE MAIN BASIN, FROM ARMSTRONG (1977)

SPECIES GROUPS OF 6 mm SIEVED SAMPLES   SPECIES GROUPS OF 1 mm SIEVED SAMPLES

Group 1

    Nephtys caeca [p]
    Scoloplos armiger [p]
    Magelona pitelkai [p]
    Tellina buttone [b]
    Macoma secta [b]

Group 2

    Mediomastus capensis [p]
    Notomastus spp. [p]
    Glycera americana [p]
    Glycera capitata [p]
    Hemipodus borealis [p]
    Glycinde picta [p]
    Platynereis bicanaliculata [p]
    Armandia brevis [p]
    Owenia fusifromis [p]
    Clinocardium nuttali [b]
    Macoma inquinata [b]
    Protothaca staminea [b]
    Saxidomus giganteus [b]
    Tresus capax [b]
    Phoronopsis harmeri [ph]

Group 3

    Capitella capitata [p]
    Lumbrineris zonata [p]
    Emplectonema gracile [n]
    Paranemertes peregrina [n]

Group 4

    Spiochaetopterus costarum [p]
    Nereis procera [p]
    Spio filicornis [p]

Group 1

    Syllides longocirrata [p]
    Pygospio elegans [p]
    Nephtys caeca [p]
    Scoloplos armiger [p]
    Paraonella platybranchia [p]

    Synchelidium shoemakeri [g]
    Lamprops quadriplicata [c]

Group 2

    Mediomastus capensis [p]
    Hemipodus borealis [p]
    Micropodarke dubia [p]
    Armanda brevis [p]
    Platynereis bicanaliculata [p]
    Spio filicornis [p]

    Unnamed Species [i]
    Allorchestes angustus [g]

Group 3

    Capitella capitata [p]
    Glycinde picta [p]
    Owenia fusiformis [p]
    Malacoceros glutaeus [p]

    Cumella vulgaris [c]
    Leptochelia dubia [t]
    Corophium acherusicum [g]
    Pontogeneia cf. ivanovi [g]
    Photis brevipes [g]

Group 4

    Notomastus spp. [p]
    Eteone longa [p]
    Pholoe minuta [p]
    Polydora columbiana [p]
    Prionospio cirrifera [p]
    Prionospio steenstrupi [p]
    Pontogeneia cf. rostrata [g]

KEY

p = polychaete annelid

b = bivalve mollusc

ph = Phoronid (phylum)

n = nemertean

g = gammarid amphipod

c = cumacean

i = isopod

t = tanaid

MEAN phi size (∅) OF SUBSTRATE (with standard deviation)

GROUP 3

GROUP 5

GROUP 6

GROUP 1 (1)

GROUP 2

GROUP 4

MEAN DEPTH (m) with standard deviation
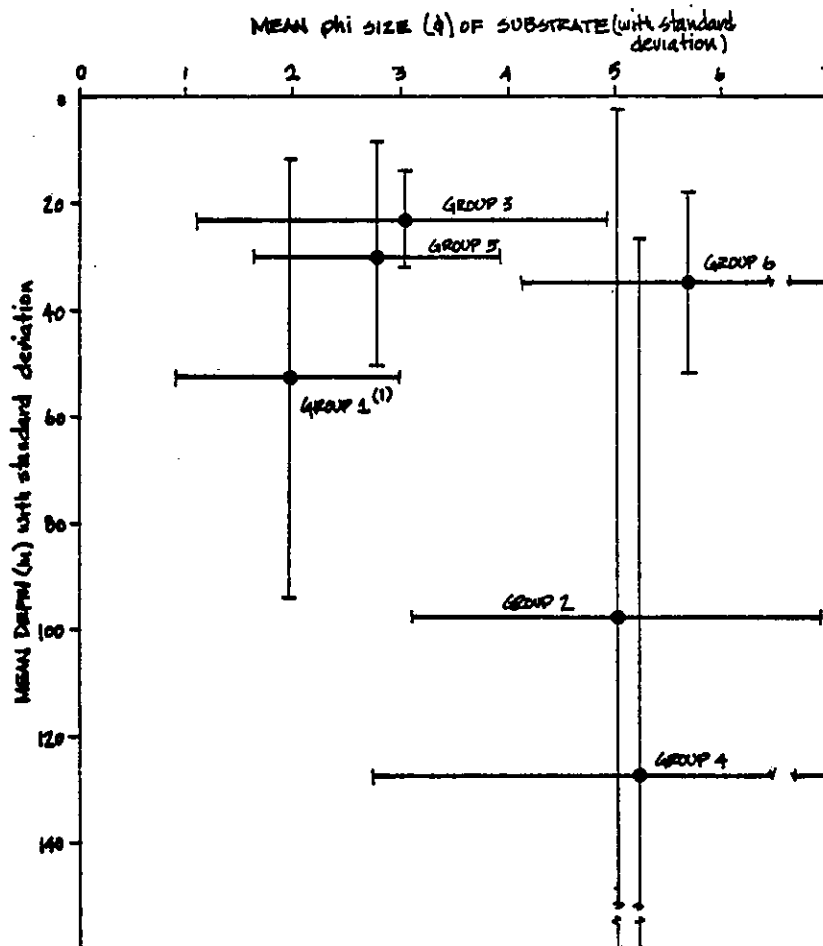
Group 1

Leptosynapta clarki[3]e[1]
Mya arenaria[3]b
Macoma incongrea b
Amphiphotis squamata[2]e
Byblis veleronis[2]g
Lyonsia pugettensis[3]b
Ophiura lutkeni[2]e

Group 2

Nucula bellotii[5]b
Axinopsida serricata[4]b
Macoma carlottensis[4]b
Euphilomedes producta[5]o

Group 3 [6]

Mysella tumida b
Psephidia lordi b

Group 3 continued

Pinnixa schmitti[cr]
Westwoodilla caecula[g]

Group 4

Pandora filosa b
Cyphocaris challengeri[a]

Group 5

Euphilomedes charcharodonta[o]

Group 6

Eudorella pacifica[c]
Pinnixa occidentalis[4]cr
Lucinoma annulata[4]
Parvalucina tenuisculpta[4]b
Compsomyax subdiaphana[4]b

(1) Groups defined by Lie (1974), using R-mode factor analysis (polychaetes) not included); see Lie and Kelly (1970) for analysis description.
(2) Species limited to stations with high percent of gravel in substrate, Lie and Kelley (1970).
(3) Species particularly abundant at stations with sandy or gravelly substrate, Lie (1968).
(4) Species found in group dominating muddy substrate, Lie and Kelley (1970).
(5) Species common at mud or muddy sand substrate, Lie (1968).
(6) Species in this group were dominant in shallow water on sand substrate, Lie (1968).
(7) e = echinoderm   cr = crab
    b = bivalve mollusc   a = amphipod
    g = gammarid amphipod   c = cumacean
    o = ostracod

Figure VI-10.   Subtidal Benthic Macrofauna Species Groups from throughout Puget Sound.

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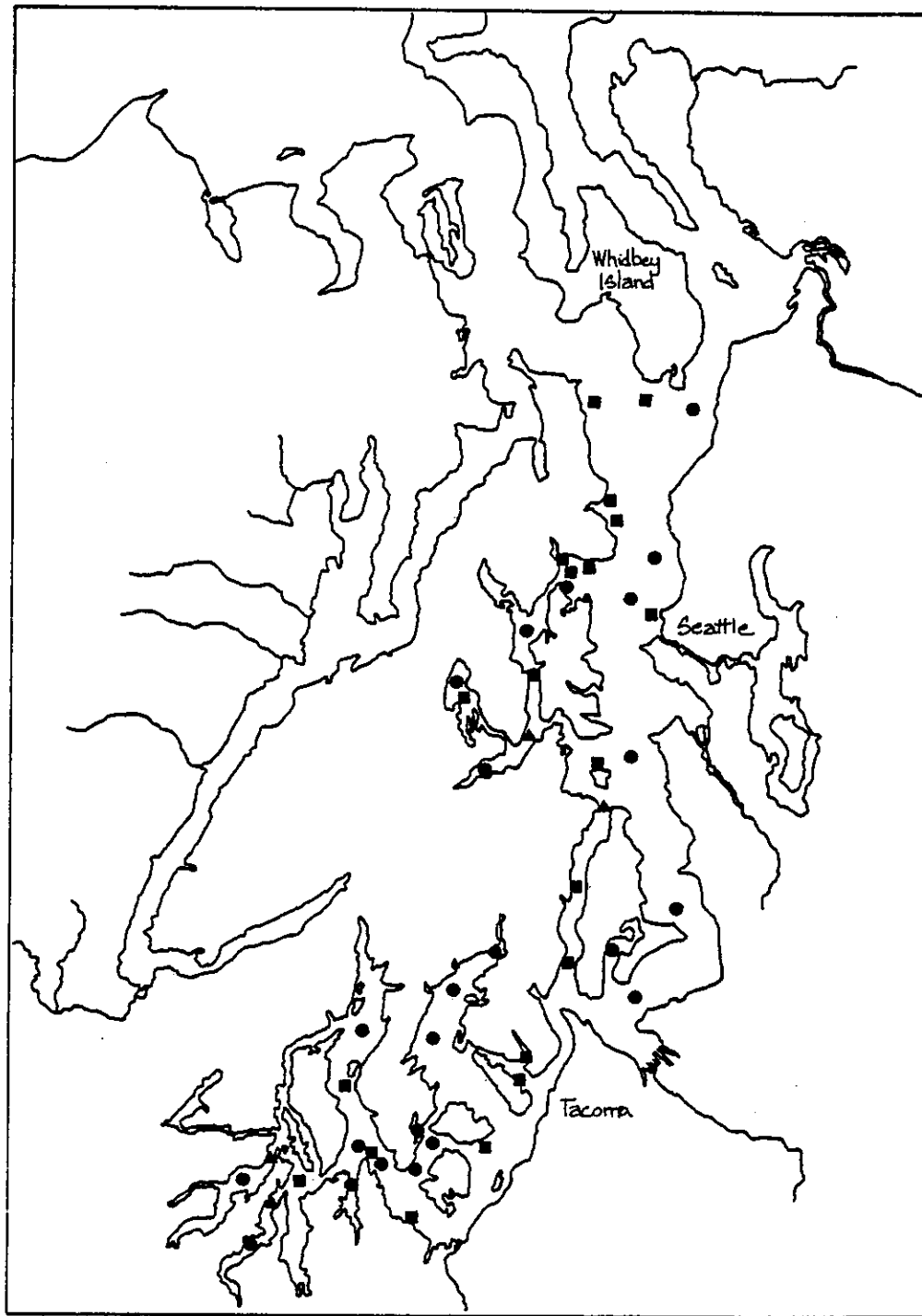
● MUD X̄ sediment size < 0.063 mm
■ SAND X̄ sediment size > 0.063 and < 2.00 mm
▲ GRAVEL X̄ sediment size > 2.00 mm

Figure VI-11. Geographic Location of Stations Dominated by Mud, Sand and Gravel Sediments.

Source: Lie, 1974.

Mud - x̄ sed size <0.063 mm
Saud - x̄ sed size >0.063 & <2.0 mm
Gravel - x̄ sed size >2.0 mm

Depth Range = 9-163 m
Sample Size = 0.2m² vanVeen
Sieve Size = 0.01 mm

Brackets represent ±95% confidence intervals
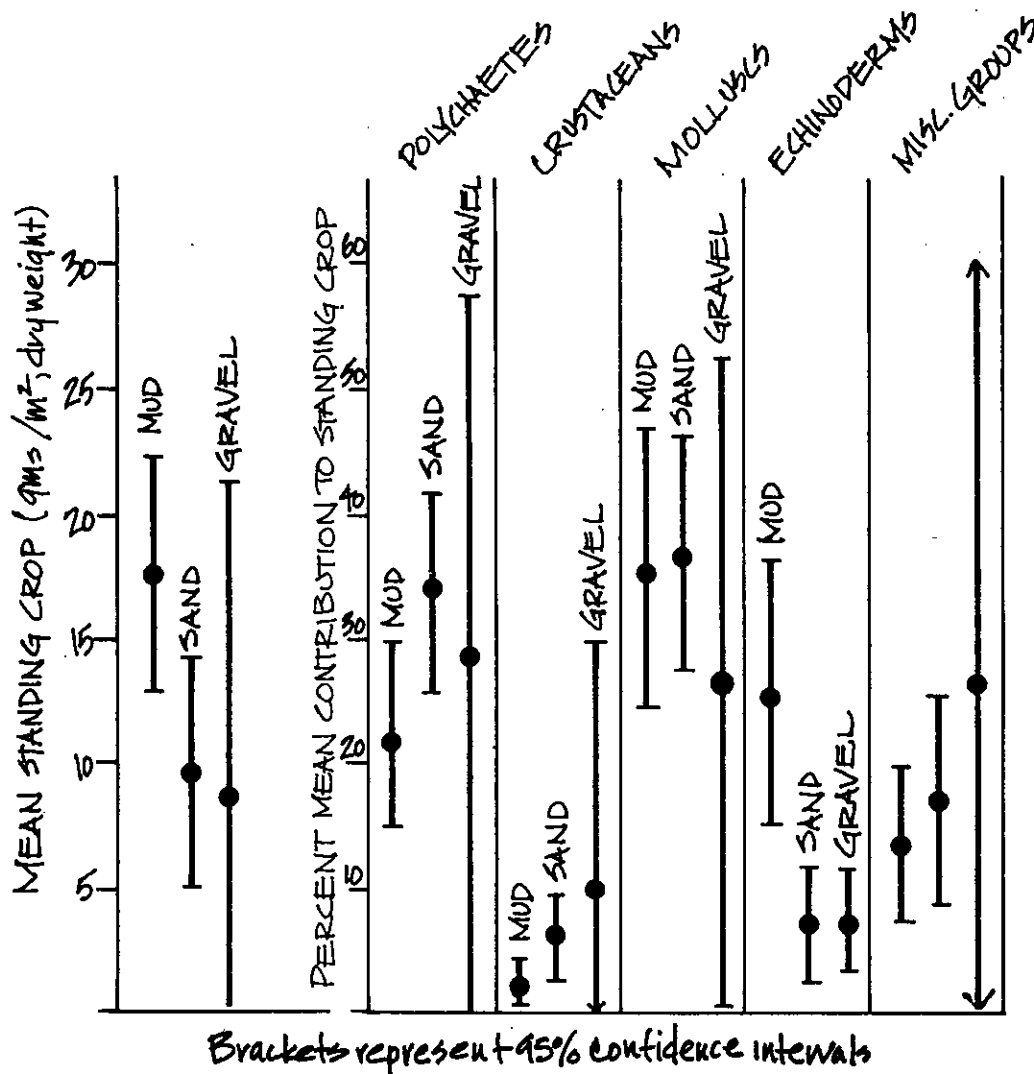
Figure VI-12. Mean Standing Crop and Percent Contribution by Major Subtidal
    Invertebrate Macrofaunal Taxa Separated by Sediment Type. Sampled
    during February-March, 1969.

Source: Lie, 1974.

TABLE VI-10

SUBSTRATE SIZE AND DEPTH COMPARISONS FOR
SUBTIDAL SPECIES GROUPS FROM FIGURE VI-10
(FROM LIE, 1974)

Groups Compared	Parameter Evaluated	Significance[1]
1 & 2	$\bar{x}$ depth	$0.10 < P < 0.20$
3 & 4	$\bar{x}$ depth	$P < 0.001$
5 & 6	$\bar{x}$ depth	$0.05 < P < 0.10$
1 & 2	$\bar{x}$ phi	$P < 0.001$
3 & 4	$\bar{x}$ phi	$0.40 < P < 0.50$
5 & 6	$\bar{x}$ phi	$P < 0.001$

(1) Using Student's "t" test, probability (P) that there is no
    significant difference between parameter x's.

Embayments - Several other intertidal and subtidal benthic fauna
studies have been conducted within the area; most of them are not
readily comparable to each other due to the aforementioned reasons.
Collectively, the results are largely inconclusive; however, tentative
trends are summarized below.

Elliott Bay - Extensive urbanization of the Elliott Bay shoreline
has eliminated most of the shallow intertidal habitats. No studies of
benthic meiofauna were located in this review. Studies of benthic
macrofauna have been located in nearshore, shallow subtidal habitats to
evaluate the effects of combined sewer overflows (Armstrong et al.,
1978) and shoreline development (Port of Seattle, 1976) or as general
surveys (Malins et al., 1980). The deep subtidal habitats have been
studied in relationship to dredged material disposal (Dexter et al.,
1979; Harman and Serwold, 1977) or general surveys (Malins et al.,
1980).

Seasonal and spatial trends in the abundance of macrofauna in Elliott Bay are shown in Figure VI-13. Stations have been grouped into Duwamish Waterway stations and Elliott Bay stations (both Alki Point and West Point stations from Malins et al., 1980 were excluded). Again, extreme variability in abundances is evident. The Duwamish Waterway stations appeared to be similar or slightly greater in mean abundance compared to Elliott Bay stations. Review of data (Malins et al., 1980, from which Figure VI-13 was drawn) shows that both the West Point and Alki Point stations have higher comparative abundances than either the Duwamish Waterway or Elliott Bay stations. These data also show that within the Elliott Bay stations, the western station (Number 10), tends to have higher abundances, a trend also reported by Harman and Serwold (1977).

Seasonal (summer and fall) increases in abundance are not as evident from the data of Malins et al. (1980); however, the trend shown in Figure VI-9 from data by Harman and Serwold (1977) is similar to that of Commencement Bay (Figure VI-13).

Species composition of Elliott Bay subtidal macrofauna is shown in Figure VI-14. Species composition does not show dramatic seasonal changes (D. Anderson, URS Company, personal communication, 1981). Similar to Commencement Bay, the most abundant bivalves are Axinopsida serricata, and Macoma carlottensis. The most abundant polychaetes are the Capitellidae, Maldanidae, Cirratulidae, and Paraonidae. Many of the same taxa were also documented by Harman and Serwold (1977), Armstrong et al. (1978), and the Port of Seattle (1975) (Figure VI-14). Comparison of results between these studies reveals differences in abundances; however, whether or not these represent actual differences or discrepancies in the taxonomic identifications is unknown.

Commencement Bay - The urbanization of Commencement Bay has also eliminated most of the shallow intertidal habitats. Sampling has been conducted for these remaining intertidal habitats in Commencement Bay (Northwest Environmental Consultants, 1973; Meyer and Vogel, 1978). Meyer and Vogel (1978) core sampled two locations in the Hylebos Waterway for benthic meiofauna in a limited study during February, 1978 (Figure VI-15). The abundance of gammarid amphipods, harpacticoid copepods, and cumaceans were all in the same range (about 10-30 thousand per m^2). Quantitative data comparisons to other meiofauna studies (Simenstad et al., 1980; Smith, 1977; and Feller, 1977), in Puget Sound are not possible due to variable sampling techniques.

The subtidal habitats of Commencement Bay have been sampled more extensively than intertidal habitats (Malins et al., 1980; U.S. Army, 1976). Seasonal and spatial trends in the abundance of
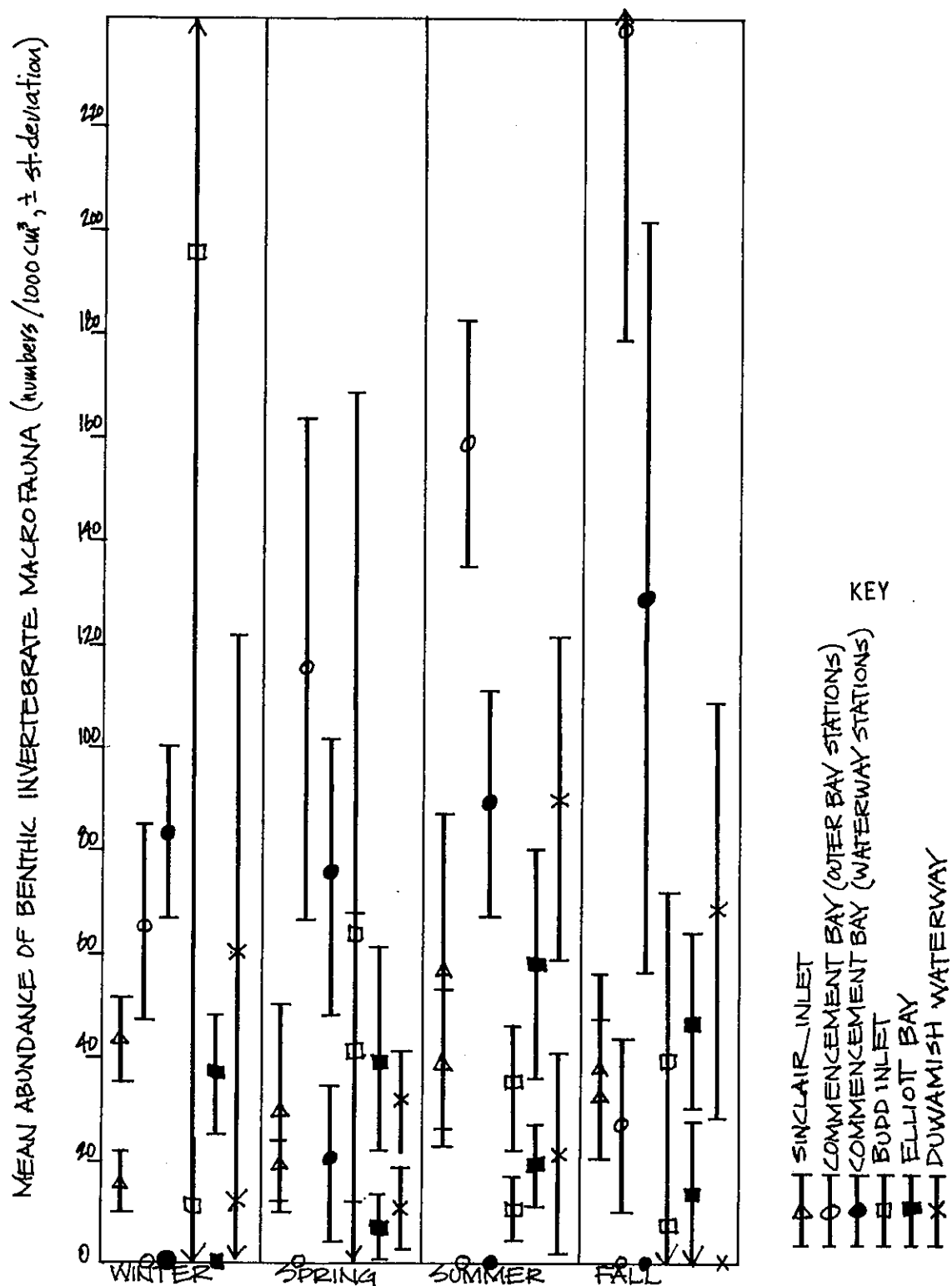
Figure VI-13. Maximum and Minimum Abundance of Benthic Invertebrate
Macrofauna Observed at Multiple Sampling Sites in Puget Sound
Embayments in Four Seasonal Samplings During 1980. a) Data are
presented by season for each embayment as the means (symbol) and
standard deviations (lines) of the abundance observed at the
stations with the maximum and minimum abundances.

Source: Malins et al., 1980, pp. 283-284.
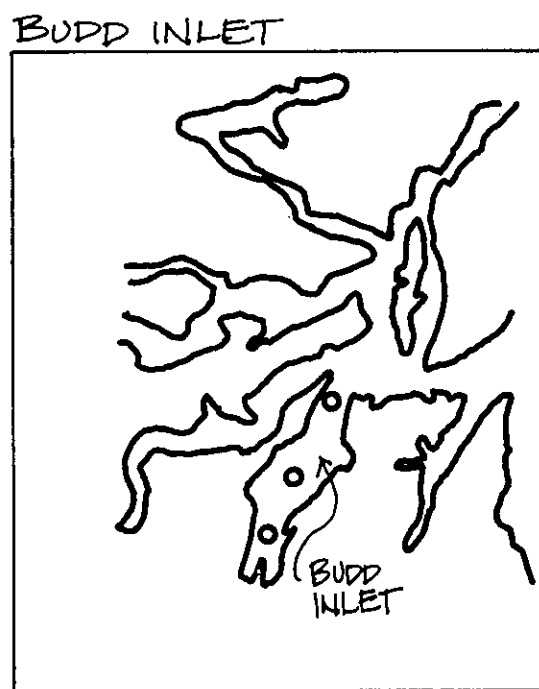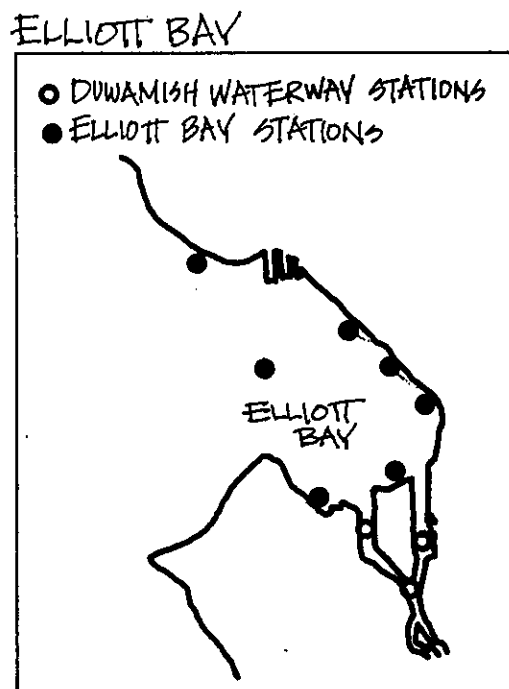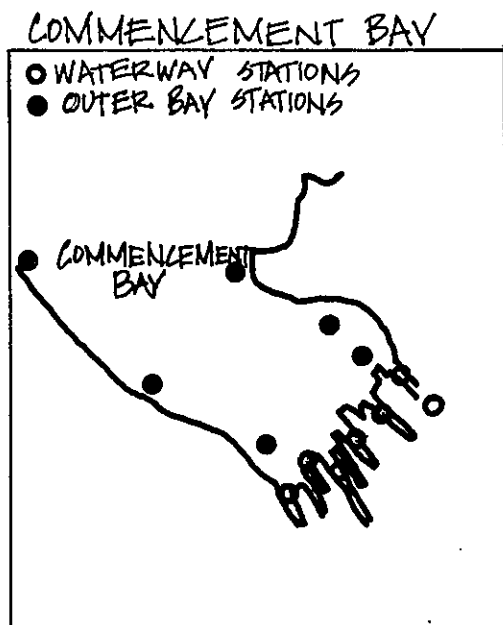
Figure VI-13 (continued) b) Approximate Locations of Stations Sampled.
The observed maximum and minimum abundances varied with season
among the stations sampled.
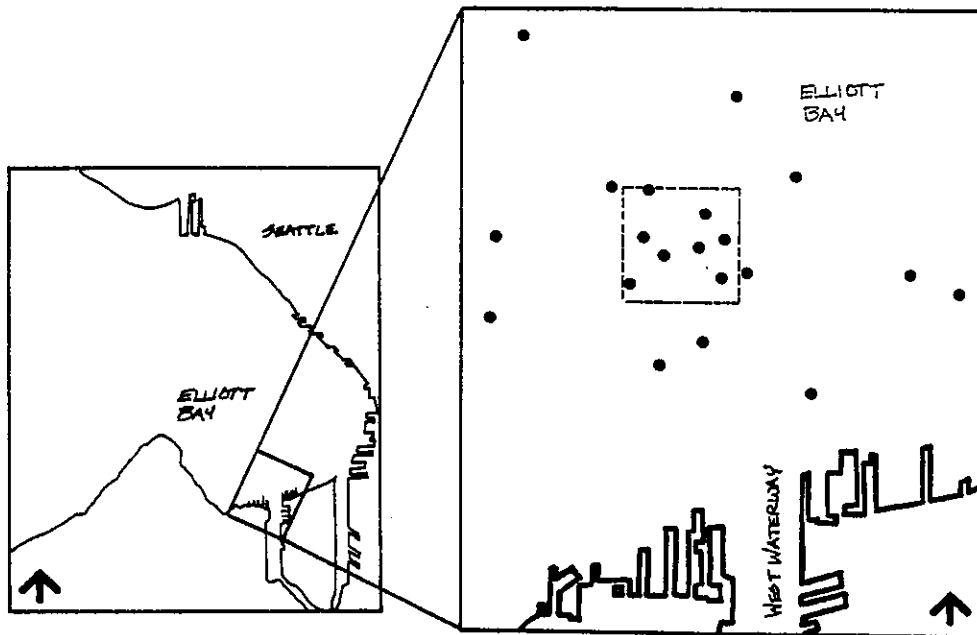
Depth Range = 50-80m

Sample Size = 0.1 m^2 VanVeen
Sieve Size = 1 mm
Sample No. = 20 (3 replicates each)

● = Station location (above)

M = Mollusc
P = Polychaete
C = Crustacean
E = Echinoderm
E* = Echiura

Taxa

Axinopsida serricata(M)*
Capitellidae spp.(P)
Mopalia intermedia (E)
Euclymeninae spp.(P)
Laonice cirrata(P)
Arhynchite pugettensis(E*)
Macoma carlottensis(M)*
Onuphis iridescens(P)
Glycera capitata(P)
Glycera americana(P)
Goniada brunnea(P)
Macoma alaskansis(M)
Praxiella gracillis(P)*
Nicomache lumbricalis(P)
Lucinoma annulata(MO)

Mean Biomass g/0.1 m^2 Sum of particular taxa abundance for all replicates divided by 60.

0.90   0.80   0.60   0.40   0.20 0.10

* = Also found abundant by Armstrong et al., (1978)

Taxa

Axinopsida serricata(M)*
Capitellidae spp.(P)
Euclymeninae spp.(P)
Paraonella spinifera(P)
Macoma carlottensis(M)*
Aricidea cf. lopezi(P)
Cossuridae sp.(P)
Lumbrineris luti(P)*
Amphipoda spp.(C)*
Nuculana minuta(M)
Prionospio cirrifera(P)*
Chaetozone setosa(P)*
Glycera capitata(P)
Nephtys ferruginea(P)*
Ostracoda spp.(C)*

Mean Abundance #'s/0.1m^2 = Sum of particular taxa wet weight for all replicates divided by 60.

300   200   100   50   0

Figure VI-14.   Ranking by Abundance and Biomass of Most Common Subtidal Macrofaunal Taxa from May 1979 Elliott Bay Cruise.

Source: Dexter et al., 1979.

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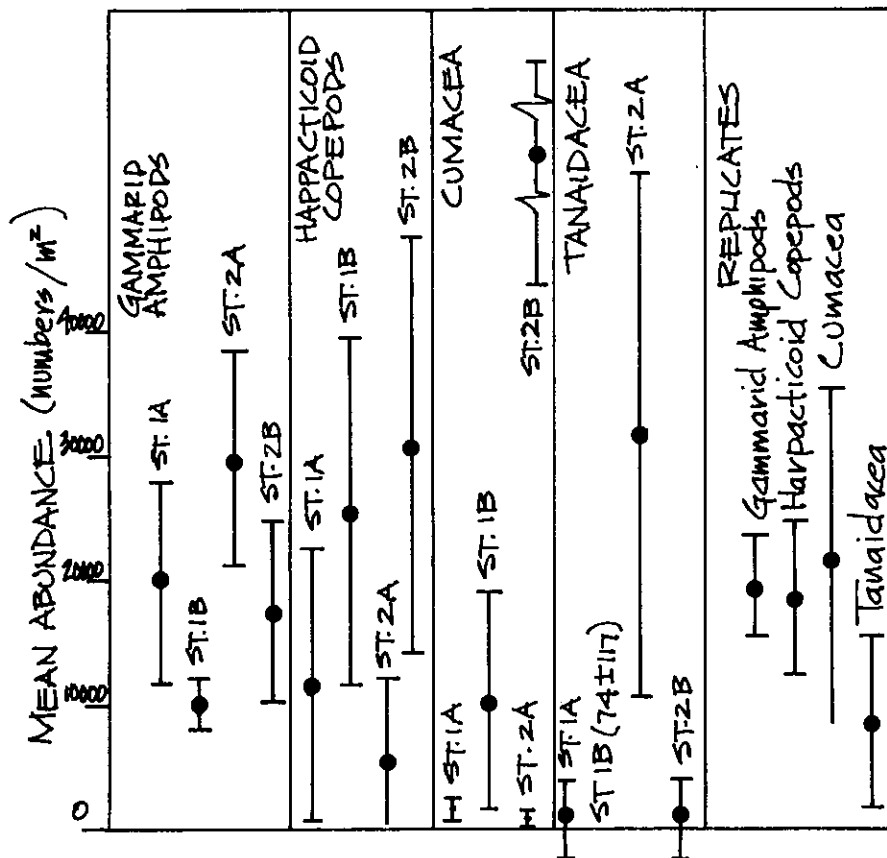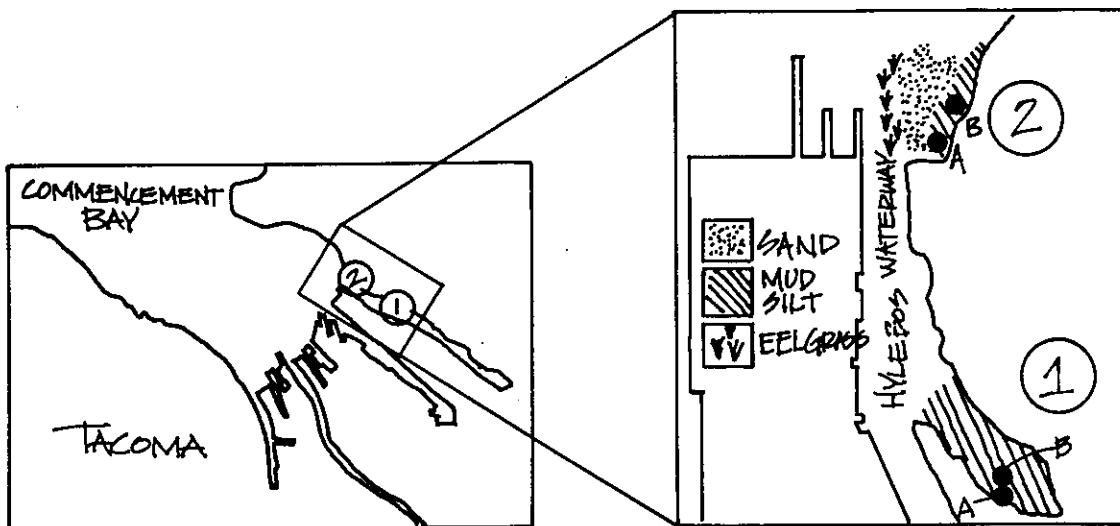
Figure VI-15. Mean Abundance of Intertidal Benthic Meiofauna for Hylebos
Waterway, Commencement Bay Sampled February 1978.

Source: Meyer and Vogel, 1978.

Figure VI-16. Mean Standing Crop of Macrofauna from Intertidal and Subtidal Habitats of Budd Inlet. Source: Beeson, 1976.

macrofauna in Commencement Bay are shown in Figure VI-13. This figure shows stations grouped spatially into waterway and outer bay categories. Most evident is the extreme variability in abundances as shown by the standard deviations. However, viewing the maximum abundances, it appears that temporally, higher abundances are seen in the summer and fall. It also appears that outer bay stations may tend to have higher abundances than waterway stations, unlike the aforementioned trend for Elliott Bay. A similar trend of higher organism abundance in offshore Commencement Bay areas was reported by the U.S. Army (1976). The authors hypothesized that this was due to high organic content and circulation patterns in nearshore waterways.

Species composition of subtidal macrofauna was dominated by the small bivalves Axinopsida serricata and Macoma carlottensis. More recent monitoring (Malins et al., 1980) has also found Axinopsida serricata and Macoma sp., as well as the Spionidae, Cirratulidae, Capitellidae, Terebellidae, and ostracods as the most abundant organisms.

Budd Inlet - Budd Inlet has been sampled less extensively than Elliott or Commencement Bays (Malins et al., 1980; Beeson, 1976). No studies of benthic meiofauna were located in this review.

The intertidal habitats of Budd Inlet are less affected by urbanization compared to Elliott or Commencement Bays.

A relative comparison of intertidal and subtidal biomass (Figure VI-16) again shows the extreme data variability. However, the mean values suggest a trend towards higher offshore standing crop, similar to that discussed for Commencement Bay abundances.

Temporal and spatial abundance data for the subtidal macrofauna are shown in Figure VI-13. Variability is great, no seasonal trends are suggested and review of the abundance data used for this plot (Malins et al., 1980) shows no apparent spatial trends.

Sinclair Inlet - The only study of benthic fauna of Sinclair Inlet focused on subtidal macrofauna (Malins et al., 1980). Figure VI-13 shows temporal and spatial abundance data. Slight increases in mean abundances are shown for the summer and fall. Actual numbers are similar in magnitude to the aforementioned embayments.

DEMERSAL FISH

Species Assemblages

The "benthic" fish discussed in this section are generally categorized by their typical habitats: demersal or bottom areas in either shallow or deep water and nearshore in shallow subtidal or intertidal areas. These fish represent a subset of the 211 fish species representing 58 families, as reported by DeLacy et al. (1972). The division between "benthic" and "pelagic" fish as defined in this text is not distinct; overlap does occur. For instance, the longfin smelt, chum salmon, ratfish, and Pacific herring all appear at one time or another in either nearshore or demersal sampling. Simenstad et al. (1979) chose 64 species which he designated as the principal components of the Northern Puget Sound region's nearshore fish community. Table VI-11 lists 46 nearshore and demersal fish species which have been commonly reported in Admiralty Inlet, the Main Basin, Port Orchard, offshore of Seattle, Colvos Passage, or Southern Sound (DeLacy et al, 1972). These species represent 15 families and include several of the more abundant species which inhabit nearshore and demersal areas. Of the species listed, those commonly utilized for sportfishing include the surf perches (Embiotocidae), rockfishes (Scorpaenidae), and flounder (Pleuronectidae). Habitats associated with some of these species are also shown in Table VI-11. Many particular species are found in several habitats, reflecting their mobility and the heterogeneity of Puget Sound habitats.

Life Cycles

Life cycles of Puget Sound benthic fish are unique to each species. Life cycle information has been summarized by Mathematical Sciences Northwest, Inc. (1977) from Hart (1973) and Beak Consultants Inc. (1975). A summary of select information from these sources is presented in Table VI-12. The eggs and larvae of most fish have been observed in pelagic waters. The exceptions are the shiner perch, striped perch, pile perch, copper rockfish, and the buffalo sculpin, which were observed in shallow, nearshore waters. In general, spawning or breeding occurs from late winter through summer. Surf perches, shiner perch, striped sea perch, pile perch, copper rockfish, yellowtail rockfish, black rockfish, bocaccio, and canary rockfish are ovoviviparous (bearing live young), while the sablefishes, greenlings, sculpins, poachers, and flounders are oviparous (egg layers).

Temporal and Spatial Changes

Several investigators have defined groups of fish as distinct assemblages (Simenstad et al., 1979; Wingert and Miller, 1979; Miller et al., 1977b). These group definitions were derived from numerical analyses based on data obtained by various sampling techniques. These sampling techniques are summarized in Table VI-13 to emphasize that groups observed from different studies may vary due to sampling differences. For the fish groups summarized below, sampling techniques will be specified.

TABLE VI-11

COMMON NEARSHORE AND DEMERSAL FISH FROM PUGET SOUND

Scientific Name	Common Name	Habitats
FAMILY ZOARCIDAE	Eelpouts	
Lycodopsis pacifica	blackbelly eelpout	
FAMILY GASTEROSTEIDAE	Sticklebacks	
Aulorhynchus flavidus	tube-snout	
FAMILY SYNGNATHIDAE	Pipefishes	
Syngnathus griseolineatus	bay pipefish	
FAMILY EMBIOTOCIDAE	Surfperches	
Cymatogaster aggregata	shiner perch	o,r,s,mc,mf,e
Embiotoca lateralis	striped seaperch	o,s,mf,e
Rhacochilus vacca	pile perch	o,r,s,m,mf,e,k,mm
FAMILY BATHYMASTERIDAE	Ronquils	
Ronquilus jordani	northern ronquil	
FAMILY STICHAEIDAE	Pricklebacks	
Lumpenus sagitta	snake prickleback	
FAMILY PHOLIDAE	Gunnels	
Apodichthys flavidus	penpoint gunnel	o,mc,mf,e
FAMILY GOBIIDAE	Gobies	
Lepidogobius lepidus	bay goby	
FAMILY SCORPAENIDAE	Rockfishes	
Sebastes caurinus	copper rockfish	o,r,s,mc,mf,e,k,mm
Sebastes flavidus	yellowtail rockfish	o,mc
Sebastes melanops	black rockfish	o,r,mc,mf,k
Sebastes paucispinis	bocaccio	o,r?,mc?
Sebastes pinniger	canary rockfish	o,r,mc
FAMILY ANOPLOPMATIDAE	Sablefishes	
Anoplopma fimbria	sablefish	o,s
FAMILY HEXAGRAMMIDAE	Greenlings	
Hexagrammos stelleri	whitespotted greenling	o,r?,m?,mc?,mf?,e?,k?
Ophiodon elongatus	lingcod	o,r,e,k
Oxylebius pictus	painted greenling	
Zaniolepis latipinnis	longspine combfish	
FAMILY COTTIDAE	Sculpins	
Artedius fenestralis	padded sculpin	
Artedius lateralis	smoothhead sculpin	
Chitonotus pugetensis	roughback sculpin	
Enophrys bison	buffalo sculpin	r
Icelinus tenuis	spotfin sculpin	
Leptocottus armatus	Pacific staghorn sculpin	o,r,s,m,mc,mf,e,k
Myoxocephalus polyacanthocephalus	great sculpin	
Nautichthys oculofasciatus	sailfin sculfin	
Radulinus asprellus	slim sculpin	
Scorpaenichthys marmoratus	cabezon	
FAMILY AGONIDAE	Poachers	
Agonus acipenserinus	sturgeon poacher	
Odontopyxis trispinosa	pygmy poacher	
Xeneretmus latifrons	blacktip poacher	
FAMILY BOTHIDAE	Lefteye Flounders	
Citharichthys sordidus	Pacific sanddab	s,m,mf
Citharichthys stigmaeus	speckled sanddab	
FAMILY PLEURONECTIDAE	Righteye Flounders	
Atheresthes stomias	arrowtooth flounder	o,s,m,mf
Glyptocephalus zachirus	rex sole	o,s,mf
Hippoglossoides elassodon	flathead sole	o,s,m,mf
Lepidopsetta bilineata	rock sole	o,s,mc,mf,e
Lyopsetta exilis	slender sole	o,s,mf,e
Microsomus pacificus	Dover sole	o,s,m
Parophrys vetulus	English sole	o,s,e
Platichthys stellatus	starry flounder	o,s,m,mf,e
Pleuronichthys coenosus	C-O sole	o,s
Psettichthys melanostictus	sand sole	o,s,mf,e

FOOTNOTES:

Sources: DeLacy et al. (1972), Mathematical Sciences Northwest, Inc. (1977)

o = open water	mf = mixed fine
r = rock	e = eelgrass
s = sand	k = kelp bed
m = mud	mm = man-made structure
mc = mixed coarse	

TABLE VI-12

LIFE CYCLE INFORMATION ON DEMERSAL FISH

Common Name	Eggs & Larvae Type	Number of eggs/ larvae	Livebearing or Egglaying	Sexually Mature Adult	Life Span	Spawning Habitat	Spawning Season
Eelpouts							
blackbelly eelpout	-	-	-	-	-	-	-
Sticklebacks							
tube-snout	-	-	-	-	-	-	-
Pipefishes							
bay pipefish	-	-	-	-	-	-	-
Surfperches							
shiner perch	NS	-	V		6	E	SP,S
striped seaperch	NS	-	V			NS	SP,S
pile perch	NS	-	V			NS	SP,S
Ronquils							
northern ronquil	-	-	-	-	-	-	-
Pricklebacks							
snake prickleback	-	-	-	-	-	-	-
Gunnels							
penpoint gunnel	D	-	-	-	-	NS,SH	W
Gobies							
bay goby	-	-	-	-	-	-	-
Rockfishes							
copper rockfish	SH	-	V	4 yrs	-	-	SP,S
yellowtail rockfish	P	HT	V	5-6	24	NS	W
black rockfish	P		V				S
bocaccio	P	2M			30	P	W,SP
canary rockfish	P	HT-M	V	5-6	22	D	W
Sablefishes							
sablefish	P	HT-M	O	-	20+	P	W,SP
Greenlings							
whitespotted greenling	P	-	O	-	-	P	S
lingcod	D	HT	O	5-F, 2-Ma	12-20	NS-D	W,S
painted greenling							
longspine combfish							
Sculpins							
padded sculpin	-	-	-	-	-	-	-
smoothhead sculpin	-	-	-	-	-	-	-
roughback sculpin	-	-	-	-	-	-	-
buffalo sculpin	NS		O				
spotfin sculpin							W,SP
Pacific staghorn sculpin							
greatsculpin	P		O	1		P	W,SP
sailfin sculpin							
slim sculpin							
cabezon	P	49-50T	O	3-4F,2-3Ma		P	SP
Poachers							
sturgeon poacher							
pygmy poacher							
blacktip poacher							
Lefteye Flounders							
Pacific sanddab	P	-	O	3-F	-	P	W
speckled sanddab							
Righteye Flounders							
arrowtooth flounder	P	6HT	O	7-13-Ma	24	NS	W
rex sole	P	1.3M	O				W,S
flathead sole	P		O	3F,2Ma		D	SP
rock sole	D		O		22-F,15-M	D	W,S
slender sole	P		O			P	SP
Dover sole							
English sole	P	HT-2M	O	4F, 3-Ma	12-18	P	W,S
starry flounder	D		O	3-F, 2-Ma		NS-D,E	W,SP
C-O sole	P		O				W
sand sole	P			3-F,2-Ma	10+	P	W,SP

Reference:

  Mathematical Sciences Northwest, Inc. (1977), Matsuda (1968)

Key:

Sh = Shallow Water	P = Pelagic	E = Estuary	W = Winter
D = Demersal Bottom	HT = Hundred Thousand	Sp = Spring	S = Summer
M = Million	F = Female	F = Fall	V = Ovoviviparous
Ma = Male	NS = Nearshore	O = Oviparous	

TABLE VI-13

COMMON NEARSHORE AND
DEMERSAL SAMPLING TECHNIQUES AND HABITATS SAMPLED

Sampling Technique	Habitat Sampled	Reference
Beach seine[1]	Within net length of shore; surface (floating net) or bottom (weighted net)	Miller et al. (1977b)
Townet[1]	Surface water in areas where boat can manuever	"
Scuba Transect	Kelp beds, rocky areas, areas with navigational obstructions	"
Otter Trawl[1]	Bottom areas at navigable depth	Miller et al. (1977a)
Drop Net[1]	Eelgrass beds	"

(1) All have variable lengths, mesh size

Figure VI-17 shows 16 assemblages of fish identified through numerical classification techniques at sites in Northern Puget Sound and the Strait of Juan de Fuca. Species which were dominant in percent occurrence, abundance, and/or biomass are also in the figure. These assemblages represent 11 shallow sublittoral, 2 littoral, 1 (rocky) sublittoral, and 2 neritic groups. Total abundances were generally 0.2-0.3 fish per m^2 (maximum of 13.1), while total fish biomass was generally 3.0-4.0 g per m^2 (maximum of 75.0) (Miller et al., 1977a). Habitat type has been documented to have an effect on fish abundance and biomass. Fish were more abundant in sand/eelgrass habitat, while biomass was highest in mud/eelgrass habitat.

Miller et al. (1977b) defined six nearshore species assemblages for the Main Basin; each one associated with a site (West Point, Point Pully, and Alki Point) and a sampling technique (Figure VI-18). A total of 87 fish species were found, however, only those comprising 70-90 percent of the total numbers of fish caught are summarized in Figure VI-18. Fish caught nearshore (beach seine) at the three Main Basin sites did not vary appreciably in species composition. Relative abundances of nearshore fish between sites were also similar with the exceptions of Pacific tomcod at West Point and Pacific herring at Point Pully. Species groups among these sites also showed similarities with

LITTORAL ZONE · **NERITIC ZONE** · SHALLOW SUBLITTORAL ZONE · ROCKY KELP BED

14
High cockscomb
Northern clingfish
Rosylip sculpin
Ringtail snailfish

1
Pacific herring[5]
Threespine stickleback[4]
Pacific sand lance
Pink salmon
Coho salmon
Tadpole sculpin

16
Surf smelt[3]
Longfin smelt
Northern anchovy
Soft sculpin

2
Yellowtail rockfish[2]
Black rockfish[2]
Copper rockfish[2]
Puget Sound rockfish[2]
Kelp greenling[2]
Lingcod[1]
Longfin sculpin[2]
Striped seaperch

15
Black prickleback
Tidepool sculpin
Mosshead sculpin
Saddleback sculpin
Fluffy sculpin
Rock prickleback
Calico sculpin
Tidepool snailfish

3
Rock sole
C-O sole
English sole[3]
Shiner perch[4,5]
Pile perch

6
Pacific staghorn sculpin[3,5]
Starry flounder
Snake prickleback
Tidepool sculpin

9
Penpoint gunnel
Cresent gunnel
Silverspotted sculpin
Whitespotted greenling
Tubenose poacher
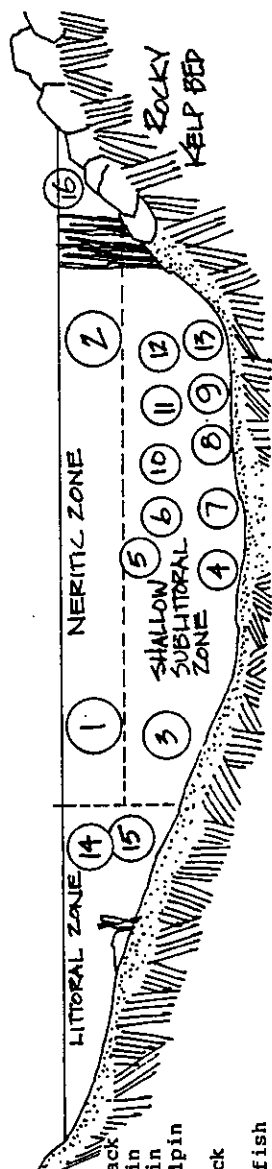
12
Copper rockfish
Smoothhead sculpin
Manacled sculpin

4
Pacific tomcod
Sturgeon poacher
Roughback sculpin

7
Sand sole
Redtail surfperch

10
Padded sculpin
Buffalo sculpin
Great sculpin
Sharpnose sculpin

13
Walleye pollock
Spiny lumpsucker
Spiny dogfish
Ratfish

5
Speckled sanddab
Pacific sanddab

8
Chum salmon

11
Tube-snout
Bay pipefish
Cabezon

(1) Data from Simenstad et al., 1979.
(2) Dominant rocky/kelp fish as reported by Miller et al., 1978.
(3) Dominant with respect to percent occurrence.
(4) Dominant with respect to abundance.
(5) Dominant with respect to biomass.

Figure VI-17. Northern Puget Sound and the Strait of Juan de Fuca Nearshore Fish Assemblages and Habitats.

SPECIES GROUPS   RELATIVE ABUNDANCE (%)   NEARSHORE FISH

Species	%
SHINER PERCH	52.1
ENGLISH SOLE	11.4
PACIFIC HERRING	10.9
ROCK SOLE	7.5
STRIPED PERCH	5.1
PACIFIC TOMCOD	2.3
STAGHORN SCULPIN	2.3
C-O SOLE	2.1
PILE PERCH	1.6
TUBESNOUT	0.7

POINT PULLY 1975-6

GROUP I C-O sole Rock sole
English sole Pacific staghorn sculpin
Shiner perch Striped perch

1/6 Padded sculpin
1/6 Pile perch
1/6 Speckled sanddab

1/6 Bay pipefish

1/12 Tomcod Sailfin sculpin

1/12 Penpoint gunnel Crescent gunnel

BEACH SEINE

SPECIES GROUPS   RELATIVE ABUNDANCE (%)   NEARSHORE FISH

Species	%
PACIFIC TOMCOD	46.0
SHINER PERCH	31.2
ENGLISH SOLE	17.8
ROCK SOLE	6.6
STAGHORN SCULPIN	1.7
STRIPED SEAPERCH	1.2
CHUM SALMON	0.6
STURGEON POACHER	0.5
PADDED SCULPIN	0.5
BUFFALO SCULPIN	0.4

WEST POINT 1975-6

GROUP I Rock sole English sole
Shiner perch Tomcod
Pacific staghorn sculpin
Buffalo sculpin

1/6 Striped perch

1/6 Starry flounder

1/12 Padded sculpin Sturgeon poacher

BEACH SEINE

Figure VI-18. Species Groups and Relative Species Abundance of Nearshore Beach Seine and Demersal Otter Trawl Fish at Three Main Basin Sites.

Source: Miller et al., 1977b.

SPECIES GROUPS[1]   RELATIVE ABUNDANCE (%)   DEMERSAL FISH

Species	%
ROCK SOLE	29.8
ENGLISH SOLE	17.3
RATFISH	12.3
ROUGHBACK SCULPIN	5.8
PACIFIC TOMCOD	2.9
PACIFIC SANDDAB	2.7
SLENDER SOLE	2.6
DOVER SOLE	2.5
TUBESNOUT	2.2
STRIPED PERCH	1.1

POINT PULLY 1975-6
(57 species, 158 samples)

GROUP I
English sole   Rock sole
Pacific sanddab   Roughback sculpin

1/4 C-O sole
1/4 Northern ronquil

1/8
GROUP II
Dover sole
Slender sole
Ratfish

1/4 Shiner perch

OTTER TRAWL

SPECIES GROUPS   RELATIVE ABUNDANCE (%)   DEMERSAL FISH

Species	%
ROCK SOLE	20.4
ENGLISH SOLE	19.4
RATFISH	11.4
STRIPED PERCH	4.4
PACIFIC TOMCOD	4.2
DOVER SOLE	4.4
C-O SOLE	4.1
ROUGHBACK SCULPIN	3.8
SLENDER SOLE	2.0
BLUESPOTTED POACHER	1.9

ALKI POINT 1975-6
(55 species, 102 samples)

GROUP I
Rock sole   English sole
Roughback sculpin

1/3 C-O sole

1/3
GROUP II
Ratfish   Slender sole
Dover sole

1/3 Blacktip poacher
1/3 Bluespotted poacher

1/4 GROUP III
Northern ronquil
Tomcod

1/3 Rex sole

OTTER TRAWL

(Cont.)
Figure VI-18. Species Groups and Relative Species Abundance of Nearshore
Beach Seine and Demersal Otter Trawl Fish at Three Main Basin Sites.
Source: Miller et al., 1977b.

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SPECIES GROUPS   RELATIVE ABUNDANCE (%)   DEMERSAL FISH

WEST POINT 1975-6
(55 species, 137 samples)

Species	Value
ENGLISH SOLE	27.1
RATFISH	26.1
ROCK SOLE	19.8
DOVER SOLE	5.7
PACIFIC TOMCOD	3.6
SHINER PERCH	3.9
ROUGHBACK SCULPIN	2.5
PACIFIC SANDDAB	1.7
C-O SOLE	1.3
REX SOLE	1.1

RELATIVE ABUNDANCE (%)   NEARSHORE FISH

Species	Value
SHINER PERCH	46.7
STRIPED PERCH	14.6
TUBESNOUT	13.6
ENGLISH SOLE	5.9
ROCK SOLE	5.2
PACIFIC TOMCOD	3.1
C-O SOLE	1.5
PADDED SCULPIN	1.1
STAGHORN SCULPIN	1.1
PILE PERCH	0.6

SPECIES GROUPS

OTTER TRAWL

WEST POINT 1975-6
(55 species, 137 samples)

GROUP I — Roughback sculpin, Rock sole
1/2 English sole
1/2 Spected sanddab
1/2 Pacific sanddab

GROUP II — Ratfish, Dover sole, Rex sole

SPECIES GROUPS (1)

BEACH SEINE

ALKI POINT 1975-6

Bay pipe fish

GROUP I — English sole, Padded sculpin, Shiner perch, Tubesnout, Pacific staghorn sculpin, Buffalo sculpin
Sailfin sculpin, Great sculpin
Pacific hake

GROUP II — C-O sole, Rock sole, Striped perch, Penpoint gunnel
Crescent gunnel
Pile perch, Tomcod
Sturgeon Poacher

(Cont.)

Figure VI-18. Species Groups and Relative Species Abundance of Nearshore Beach Seine and Demersal Otter Trawl Fish at Three Main Basin Sites.

Source: Miller et al., 1977b.

shiner perch, English sole, and Pacific staghorn sculpin occurring together. A comparison between these data and the fish observed in the shallow sublittoral habitat of the Northern Sound shows many similarities (e.g., groups 3, 4, and 7, Figure VI-17). The fish caught in offshore, bottom areas (otter trawl) at these sites were also quite similar in species composition, relative abundances and species groups.

Although the above data are specific to sites and sampling techniques, some species have a tendency to be located in particular habitats. Table VI-14 shows the habitat preferred by some of the more abundant fish of the Main Basin.

Embayments - Demersal and nearshore fish data for three of the four embayments are limited to that of Malins et al., 1980. Elliott Bay, the fourth embayment, has been studied more extensively (Malins et al. 1980; Miller et al., 1977b; Matsuda, et al. 1968). Fish data for each embayment are summarized below.

Elliott Bay - The average abundances of demersal fish in Elliott Bay at all depths (Figure VI-19) have been observed to be similar from season to season with a slight increase in the fall. However, Hughes et al. (1978) reported an apparent seasonal flux in fish abundance in the subtital habitat of Elliott Bay. Abundance data from otter trawls at a depth of about 60 m (Figure VI-20) showed a trend of higher abundances in the late winter and early spring months. Sampling variability was high, as evidenced by the 95 percent confidence intervals for the three replicate samples. This trend for higher total abundances in the winter and early spring in deeper water was also found at three sites in the Main Basin by Miller et al., 1977b (Figure VI-21). This seasonal bathymetric shift was attributed to English and rock sole by Miller et al. (1977b). The temporal (seasonal) and spatial (bathymetric) trends for the most abundant demersal fish are shown in Table VI-15. Both the English and rock sole are found in the four embayments during all seasons. These species, among others, were selected as target species for histopathological analyses by Malins et al., 1980. Deep water sampling of Elliott Bay revealed that both of these species are also abundant at depths of 60 - 300 ft.

The Duwamish River Estuary was sampled by Miller et al. (1977b) who caught 29 fish species (beach seines). More than 70 percent of the samples had English sole and the Pacific

TABLE VI-14

SELECTED DEMERSAL AND NEARSHORE FISH AND ASSOCIATED HABITATS
IN THE MAIN BASIN (1)

Demersal Fish (bottom-associated)	Nearshore Fish (water-column-associated)

Flounders

    English sole (2,3,4)
    Rock sole (2,5)
    C-O-sole (2,6)
    Dover sole (7)
    Rex sole (7)
    Slender sole
    Pacific sanddab
    Speckled sanddab (2,6)

Sculpins

    Roughback sculpin (2,3)
    Pacific staghorn
      sculpin (2,3,4,9)
    Padded sculpin

Others

    Penpoint gunnel (10)
    Northern ronquil
    Sturgeon poacher

Perch

    Shiner perch (2,3,9,10,11,12)
    Striped seaperch (6,10)
    Pile Perch (2)

Others

    Pacific tomcod (2,3,11)
    Ratfish

KEY:

(1) List from Wingert and Miller (1979)
(2) Diel migratory tendency - Deep (day) to Shallow (night) Cooney
(1967)
(3) Eurybathic fish
(4) Dominant in percent frequency of occurrence in Northern Puget
Sound along with Surfsmelt (Miller et al., 1977a).
(5) Dominant of Nisqually Delta (Fresh et al., 1979)
(6) Shallow water fish (Cooney, 1967; Wingert et al., 1979)
(7) Deep water fish (Cooney, 1967; Wingert et al., 1979) (8) Dominant
in biomass in Northern Puget Sound along with Pacific herring
(Miller et al., 1977a)
(9) Dominant off Nisqually Delta along with starry flounder and Pacific
herring (Fresh et al., 1979)
(10) Associated with eelgrass
(11) Associated in near-surface (neritic) waters
(12) Dominant in abundance in Northern Puget Sound along with Pacific
sand lance (Miller et al., 1977a).
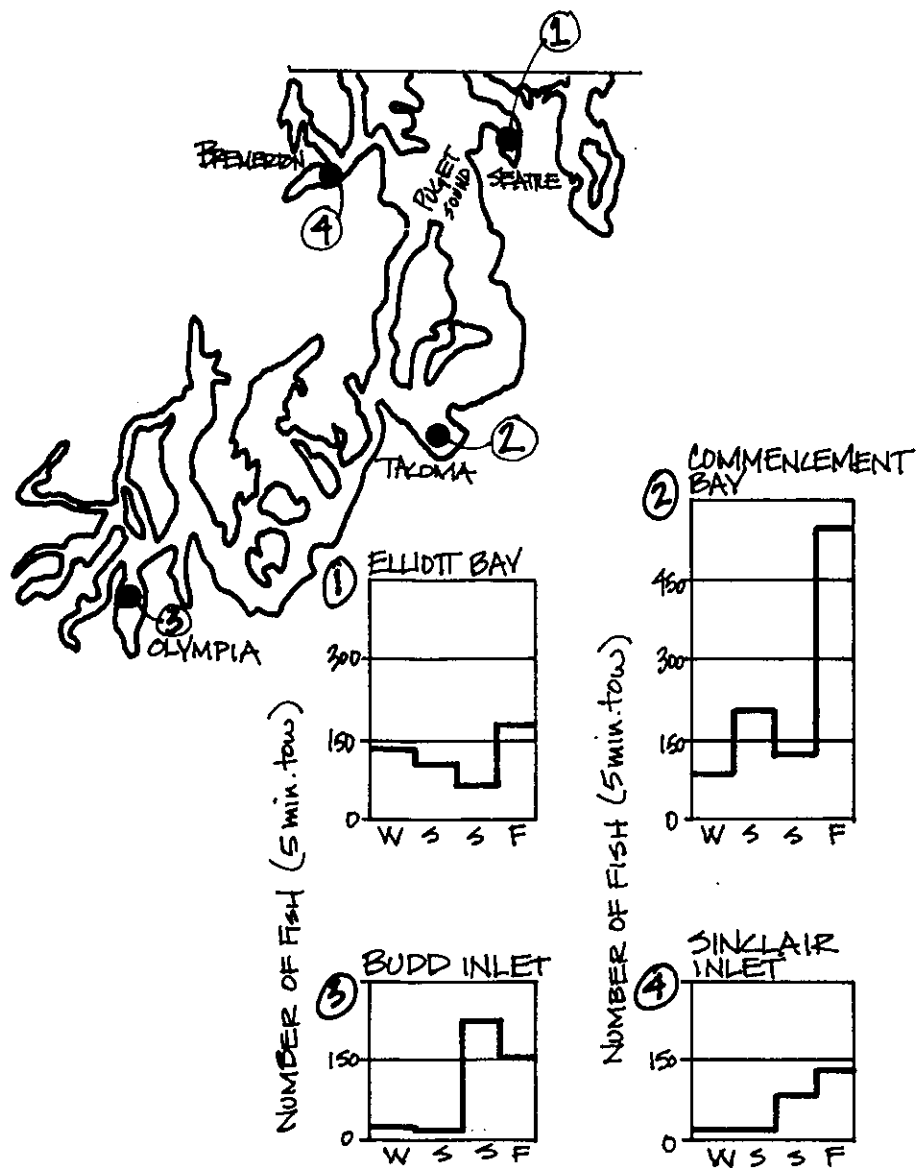
Figure VI-19. Average Catch Per Unit Effort (CPUE) for Demersal Fish in Selected Embayments of Puget Sound.

Modified from Malins et al., 1980.
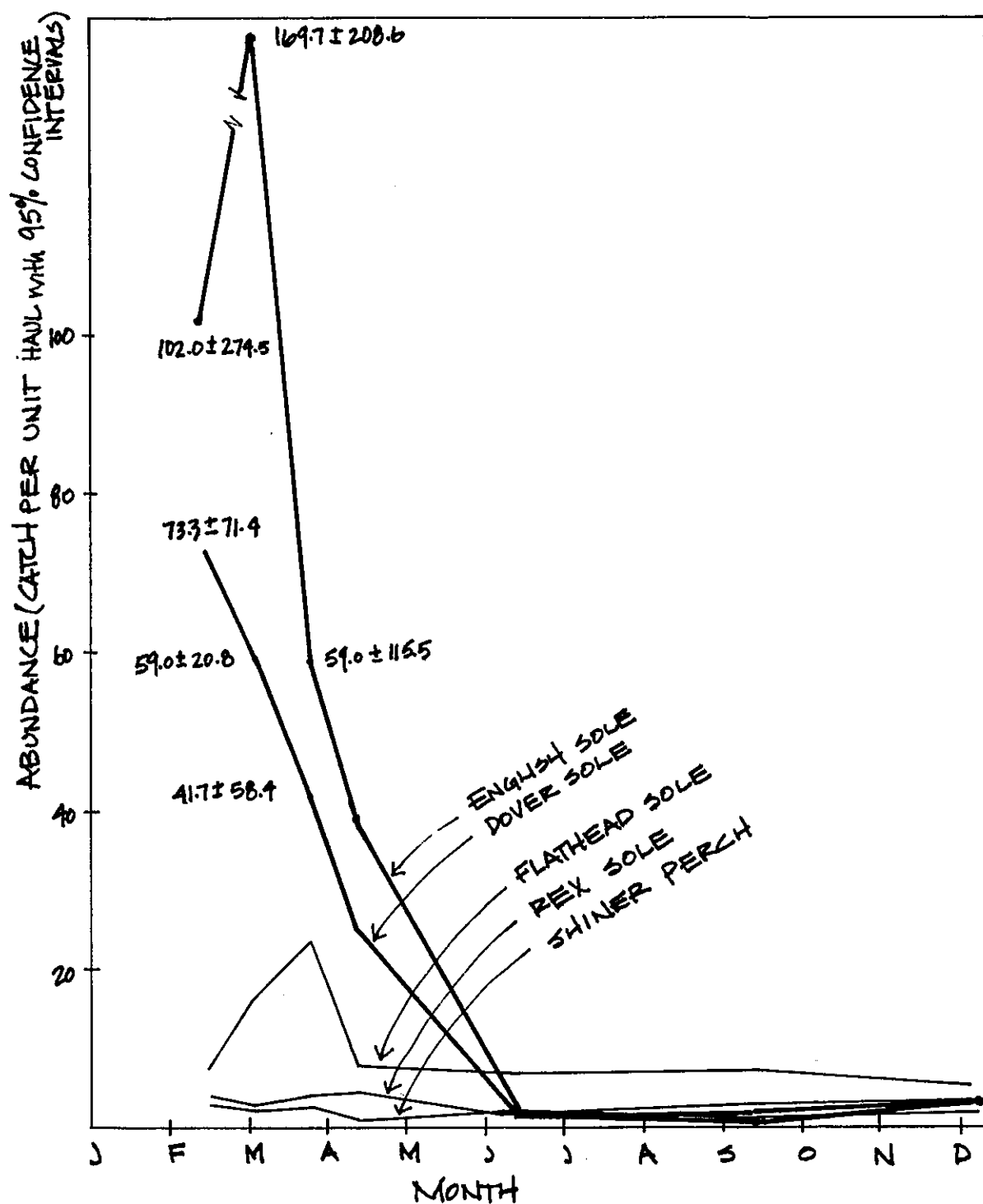
Figure VI-20. Seasonal Variation in Abundance of Select Fish in Elliott Bay.

Source: Hughes et al., 1978.
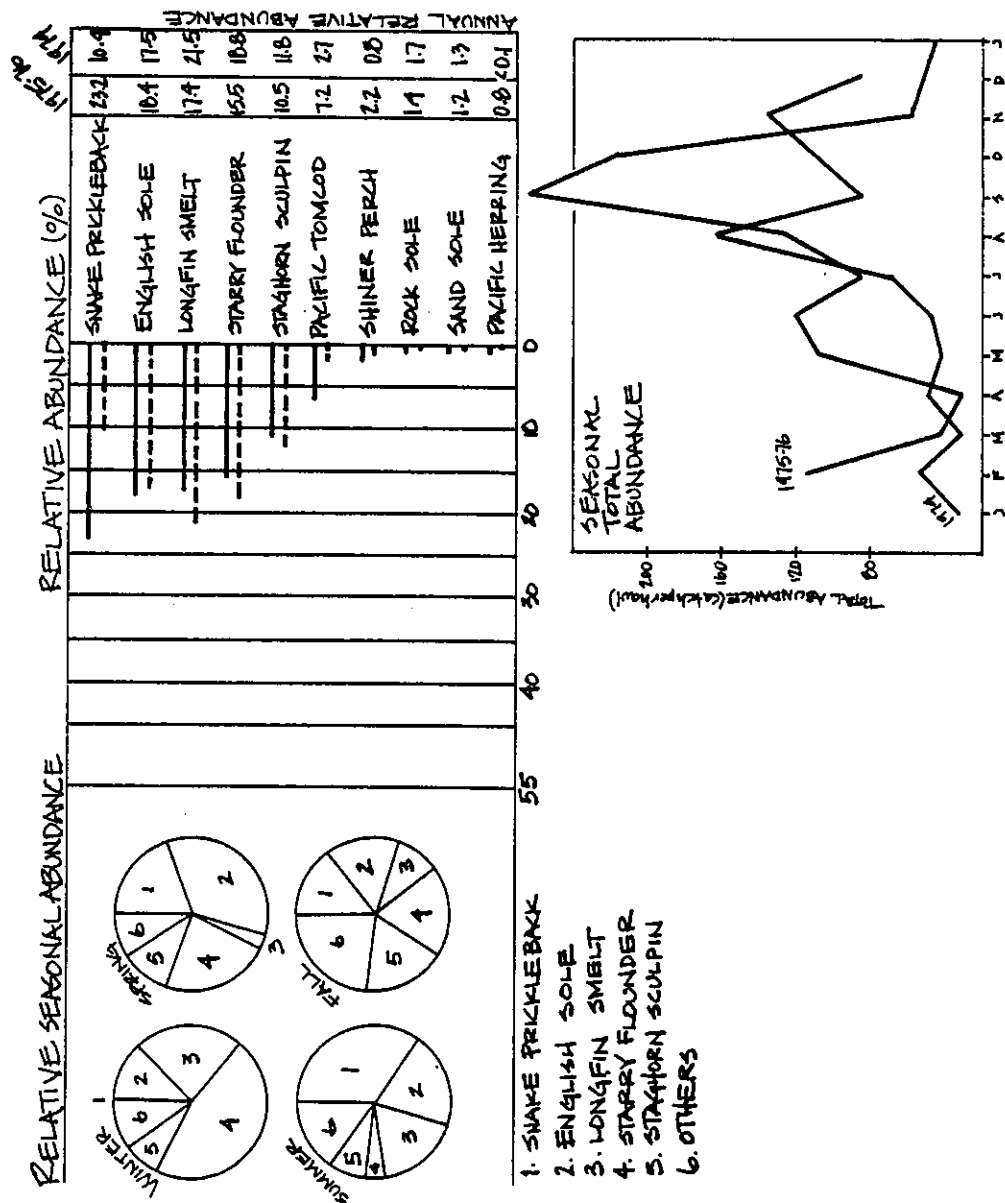
Figure VI-21. Seasonal and Annual Variation in Total and Relative Abundance
of Duwamish River Estuary Fish.

Source: Miller et al., 1977b; Matsuda, 1968.

TABLE VI-15

TEMPORAL AND SPATIAL DISTRIBUTION OF THE MOST ABUNDANT
SPECIES IN SELECTED EMBAYMENTS (1)

TAXA	Winter Shallow[2]	Winter Deep[3]	Spring Shallow[2]	Spring Deep[3]	Summer Shallow[2]	Summer Deep[3]	Fall Shallow[2]	Fall Deep[3]
Eelpouts								
blackbelly eelpout				O	●	O		O
Surfperches								
shiner perch	O●	O	●	O	■		O●□■	
pile perch			O		■		●■	
Pricklebacks								
snake prickleback			O ●		O□		O■■	
Ronquils								
northern ronquil				O				
Gobies								
bay goby					O□		O●	O
Rockfishes								
copper rockfish	■							
quillback rockfish		O		O				
brown rockfish	■		■					
Sculpins								
roughback sculpin	□	O	O□■	O		O	O□	
Pacific staghorn sculpin[4]	O●□		O●		●□■		●□■	
Lefteye Flounders								
speckled sandab	□		□■		□		□	
Righteye Flounders								
flathead sole	O●	O	●	O	O●	O	●	O
rock sole[4]	O●□■	O	O●□■	O	O●□■	O	O●□■	O
Dover sole				O	O●	O	O	O
English sole[4]	O●□■	O	O●□■	O	O●□■	O	O●□■	O
starry flounder	□■		O●□■		●□■		□	
C-0 sole			□					
sand sole	O●□■		O●□■		O□■		□■	
slender sole						O		
rex sole		O				O		O

O = Elliott Bay   ● = Commencement Bay   □ = Budd Inlet   ■ = Sinclair Inlet

(1) Data from Malins et al., 1980, Appendix G. Species deleted from listing include longfin smelt, herring, Pacific tomcod, ratfish.

(2) Shallow waters at ≤ 50 feet.

(3) Only Elliott Bay data, of the four embayments discussed herein, are reported for deep waters (60 - 300 ft).

(4) Target species of Malins et al. (1980).

staghorn sculpin. Figure VI-21 shows the relative abundance of species. Matsuda et al. (1968) reported 28 species in the Duwamish waterway. Seasonal and annual changes in the relative abundance of dominant fish in the Duwamish River Estuary are also shown in Figure VI-21. Both longfin smelt and snake prickleback are seasonal residents of the estuary with English sole, Pacific staghorn sculpin and starry flounder being year-round residents. Data from Malins et al., 1980 (Figure 55, page 166) show that during the winter and spring, greater than 50 percent of the English sole are juveniles ($\leq$ 150 mm) in the Duwamish River Estuary. Species composition exhibited similar relative abundances between years. Seasonal trends in total abundance for the shallow Duwamish River Estuary shows summer and early fall peaks compared to the fall peak for Elliott Bay (Figure VI-19). English sole were most abundant in the lower portion of the estuary with starry flounder most abundant in the upper estuary (Miller et al., 1977b; Matsuda et al., 1968). Shiner perch and Pacific staghorn sculpin also had higher abundances in the lower estuary; shiner perch having peak abundances in summer corresponding to young bearing.

Commencement Bay - Commencement Bay exhibit a large peak of demersal fish in the fall (Figure VI-19). Seasonal trends for particular species (Table VI-15) reveal year-round occurrence for Pacific staghorn sculpin, flathead sole, rock sole, and English sole.

Budd Inlet - Budd Inlet also experienced peak abundances of demersal fish in the summer and fall (Figure VI-19). Unlike Elliott and Commencement Bays, the starry flounder and speckled sanddab were found in all seasons in Budd Inlet. Similar to these above bays, rock sole and English sole were abundant year-round. The proportion of juvenile English sole was greater than 50 percent of the total fish caught during the winter, spring, and fall of 1979 (Malins et al., 1980).

Sinclair Inlet - Sinclair Inlet showed similar trends for higher abundance of demersal fish in the summer and fall (Figure VI-19). Rock sole, English sole and sand sole were abundant year-round (Table VI-15).

The preceding data present a complex scenario from which few clear generalizations are possible. Most of the organisms observed are undoubtedly migratory animals whose distribution shifts in response primarily to prey/food availability, predator avoidance strategies, physical stresses, and natural population variability. Thus there is a general trend toward larger and older fish in deeper water since larger predators are excluded from the shallow zones. Similarly, there is an apparent general seasonal migration to deeper water, probably to avoid the winter cold and turbulence of the shallows. This latter trend may also partially reflect the

seasonal changes in the occurrence of young, small fish, which as noted, favor the shallows.

Only in certain cases have studies indicated that habitat characteristics have a major influence on the benthic community. For example, Wingert and Miller (1979) observed that eelgrass beds may support a different nearshore fish community than other areas.

In addition, offshore fish tend to shift in community assemblages toward a clearer distinction between demersal and pelagic organisms, reflecting the fact that in nearshore areas the shallow depth greatly increases the relative importance of benthic food sources compared to water-column sources (e.g., plankton).

Finally, it may be important to note that many if not most of the fish group assemblages identified in these studies (e.g., Figures VI-17 and VI-18) consist predominately of competitors for the same or closely overlapping ecological niches, i.e., food and cover. This further supports the observation that food, physical characteristics of the area, and natural population variability are more important in determining the fish percent in an area than are the development of strong complementary assemblages associated with specific sites or habitats.

NEARSHORE MARINE BIRDS

As was the approach taken with the fish, the information on birds in the study area is divided into two groups. The data presented here address those species which reside and feed nearshore. Those birds that primarily reside and feed offshore are included in the previous chapter. Data germaine to this report are very limited at this time, but support the following observations.

Species Assemblage

The families represented in this category are Ardeidae, Charadriidae, Scolopacidae, Phalaropodidae, Accipitridae, Pandionidae, and Alcedinidae and are presented in Table VI-16.

Life Cycles

The majority of the birds that reside and feed nearshore are migrants that pass through the area during the spring and fall. A few species, the great blue heron, killdeer, and belted kingfisher, are year-round residents in the Puget Sound. Nests of the belted kingfisher and killdeer have been observed in the area. Detailed descriptions of the life cycles of these nearshore birds can be found in Salo (1975) and Eaton (1975).

Temporal and Spatial Changes

The seasonal occurrence of select nearshore birds is shown on Table VI-16. The majority of the species are winter migrants with the exception of the ruddy turnstone, whimbrel, greater yellow-legs, pectoral sandpiper, long-billed dowitcher, western sandpiper, Wilson's phalarope plovers, bald eagle, and osprey which are fall and spring migrants, and the killdeer and belted kingfisher, which nest in the Southern Sound.

The spatial occurrences of these species are also shown in Table VI-16. All but one species (pectoral sandpiper) have been observed in Commencement Bay.

Both the great blue heron and the osprey are listed on the Audubon Societie's Blue List of species whose abundance in all or part of their range is decreasing (Eaton, 1975). No studies were identified which indicated the cause(s) of these decreases.

No recent population studies on birds within the Main Basin and/or Southern Sound could be located during the preparation of this report (D. A. Manuwal, Forestry Resources, University of Washington, and

TABLE VI-16

NEARSHORE BIRDS OF PUGET SOUND

A. Shorebirds

Family	Common Name	Scientific[1] Name	Location[2] E	C	B	S	Season[2] F	W	Sp	Su
ARDEIDAE	Great blue heron	Ardea herodias	X	X		X	X	X	X	X
CHARADRIIDAE	Killdeer	Charadrius vociferus vociferus	X	#		X	X	X	X	X
	Black-bellied plover	Pluvialis squatarola	X				X	X	X	
	Surfbird	Aphriza virgata	X				X	X	X	
SCOLOPACIDAE	Ruddy turnstone	Arenaria interpres	X							X
	Black turnstone	Arenaria melanocephala	X	X			X	X	X	
	Whimbrel	Numenius phaeopus	X						X	
	Spotted sandpiper	Actitis macularia	X	X		X	X	R	X	
	Greater yellowlegs	Tringa melanoleuca		X			X		X	
	Pectoral sandpiper	Calidris melanotos			X		X		X	
	Least sandpiper	Calidris minutilla	X	X			X	R	X	
	Dunlin	Calidris alpina	X	X		X	X	X	X	
	Long-billed dowitcher	Limnodromus scolopaceus	X				X		X	
	Sanderling	Calidris alba	X	X	X	X	X	X	X	
	Western sandpiper	Calidris mauri	X	X	X	X	X	X		
PHALAROPODIDAE	Wilson's phalarope plover	Steganopus tricolor	X				X	X		

B. Casual Marine Feeders

Family	Common Name	Scientific[1] Name	Location[2] E	C	B	S	Season[2] F	W	Sp	Su
ACCIPITRIDAE	Bald eagle	Haliaeetus leucocephalus	X				X	X		
PANDIONIDAE	Osprey*	Pandion haliaetus	X				X	X		
ALCEDINIDAE	Belted kingfisher	Megaceryle alcyon	#	X			X	X	X	X

LEGEND

1 - Larrison and Sonnenberg, 1968

2 - Salo, 1975

X - Documented observation
* - Included on Audubon Society's "Blue List" (Washington Environmental Atlas, 1975)

- Nest sites observed (Salo, 1975)

E - Elliott Bay   F - Fall
C - Commencement Bay W - Winter
B - Budd Inlet   Sp - Spring
S - Sinclair Inlet   Su - Summer

3 - R = Rare

R. Hirschi, Washington Department of Game, personal communication). A
multi-year, semi-quantitative survey from ferry boat observations has
been performed but the data have not been assembled or analyzed at this
time (R. Hirschi, personal communication). Similarly, the local chapters
of the Audubon Society have performed winter surveys (Christmas Day) in
Elliott and Commencement Bays and Budd and Sinclair Inlets for a number
of years, but these data have not been compiled into a useful form.

Polychaetes, molluscs, amphipods, benthic invertebrates, and other
small crustaceans compose the major food source for birds that feed
nearshore in the Strait of Juan de Fuca and the San Juan Islands (Simenstad
et al., 1979). It is assumed that the feeding habits of birds are
similar while they are migrating through the study area.

SUMMARY: BENTHIC BIOTA

The benthic floral community in Puget Sound is constituted of
seagrasses, benthic microphytes and macroalgae; while the fauna include
benthic invertebrates, demersal fish and nearshore birds.

Annual production of the attached floral community appears to be
related to insolation and air temperature, with peak standing stocks
occurring in late summer to early fall. Spatial changes in the species
composition and standing stock of the flora have been hypothesized to be
controlled by the bottom/substrate/composition and stability, available
sunlight (affected by water depth and turbidity), temperature, salinity,
predation and the emergence times of the plants. This hypothesis has
received limited testing.

Overall, benthic floral production appears to be only a small
fraction of the phytoplankton production; however, precise quantitative
measures are lacking. In nearshore areas, the rooted plants may consti-
tute a major food source as well as habitat for many important fish and
invertebrates.

The benthic invertebrate fauna of the intertidal habitats of Puget
Sound appear to exhibit greater species richness than those of comparable
subtidal areas. However, the subtidal taxa have been noted to be richer
in different species than observed in subtidal sites in other estuaries
at similar latitudes. Studies of the benthic meiofauna and microfauna
are limited for the study area. The spatial distribution of benthic
macrofauna appears to be affected by the species' response to substrate
composition and water depth; however, discrete subtidal communities
associated with particular habitats do not appear to exist in Puget
Sound.

Synoptic surveys of the subtidal benthic macrofauna of Puget Sound, performed during late winter, found total standing crops of between 10 g/m^2 and 17 g/m^2 (dry weight), with about 35 percent and 25 percent of the biomass accounted for by molluscs and polychaetes, respectively. In general, both abundances of the organisms and the total biomass tend to increase to maxima during the late summer to fall. However, temporal changes in individual species show much more complex seasonal and yearly variations which are poorly understood.

The benthic invertebrates support a diverse fish community, which, as noted in Chapter 5, probably includes many species which are dominantly pelagic, but at least during portions of their life cycle are bottom feeders. The demersal fish may be particularly vulnerable to toxic chemicals because of their dominant association with the bottom and with nearshore areas. As noted in Chapters 8, 9 and 10, the highest concentrations of many toxic chemicals have been observed in the sediments and most abnormalities have been observed in benthic organisms. At the same time, very little is known regarding the productivity and/or details of the life cycles of most demersal fish species.

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CHAPTER 7.   FOOD WEB

This chapter addresses both of the previous two biological sections (pelagic and benthic) to provide an overall perspective of the Puget Sound food web.

A schematic representation of the important components of the overall Puget Sound food web is shown in Figure VII-1. The primary producers (benthic flora and phytoplankton) provide a direct carbon source to consumers as well as an indirect carbon source composed of detritus. As shown in the previous sections, the biota in Main Basin and embayment intertidal and subtidal habitats are similar. This would suggest that the nearshore and demersal food web, as well as the pelagic food web, between the Main Basin and embayments would also be similar.

The nearshore and demersal food web is largely not dependent on the pelagic food web. However, migration of nekton and exchange of planktonic components create an overlap. For example, salmonid migration links the pelagic to the nearshore and demersal food web through dependence of juveniles on epibenthic organisms. The pelagic portion of the food web is based principally on autotrophic production. The benthic food web (nearshore and demersal habitats) is based on detritus or a combination of autotrophic production and detritus.

The importance of detritus to the overall food web relationship in Puget Sound cannot be overstated. Detritivores are the major prey organism for higher trophic levels in Northern Puget Sound (Simenstad et al., 1979). This is probably true in the Main Basin and embayments, as indicated by the predominance of detritivorous infauna for intertidal (Armstrong, 1977) and deep subtidal areas (Dexter et al., 1979). Besides supporting the benthic community, detritivores, such as harpacticoid copepods, polychaetes, and gammarid amphipods, are important for the feeding of larval and juvenile fish, especially salmonids (Simenstad and Lipovsky, 1976; Gerke and Kaczynski, 1972) and this resource probably constitutes the major source of energy to the pelagic food chain in nearshore areas during the early spring (Fresh et al., 1979; Simenstad et al., 1979). Sessile forms of benthic fauna may be dependent on a detrital substrate for successful larval settling. Selective settling may be influenced by the content of organic material adhering to or between mineral grains in the substrate (Thorson, 1957).

Although quantitative data are scarce, there is also evidence that together detritus, dissolved organic carbon, bacteria, nanoflagellates, protozoa, and meroplanktonic larvae are responsible for the main fraction of energy flow through the pelagic food web, particularly during winter when conditions are unfavorable for larger phytoplankton and zooplankton
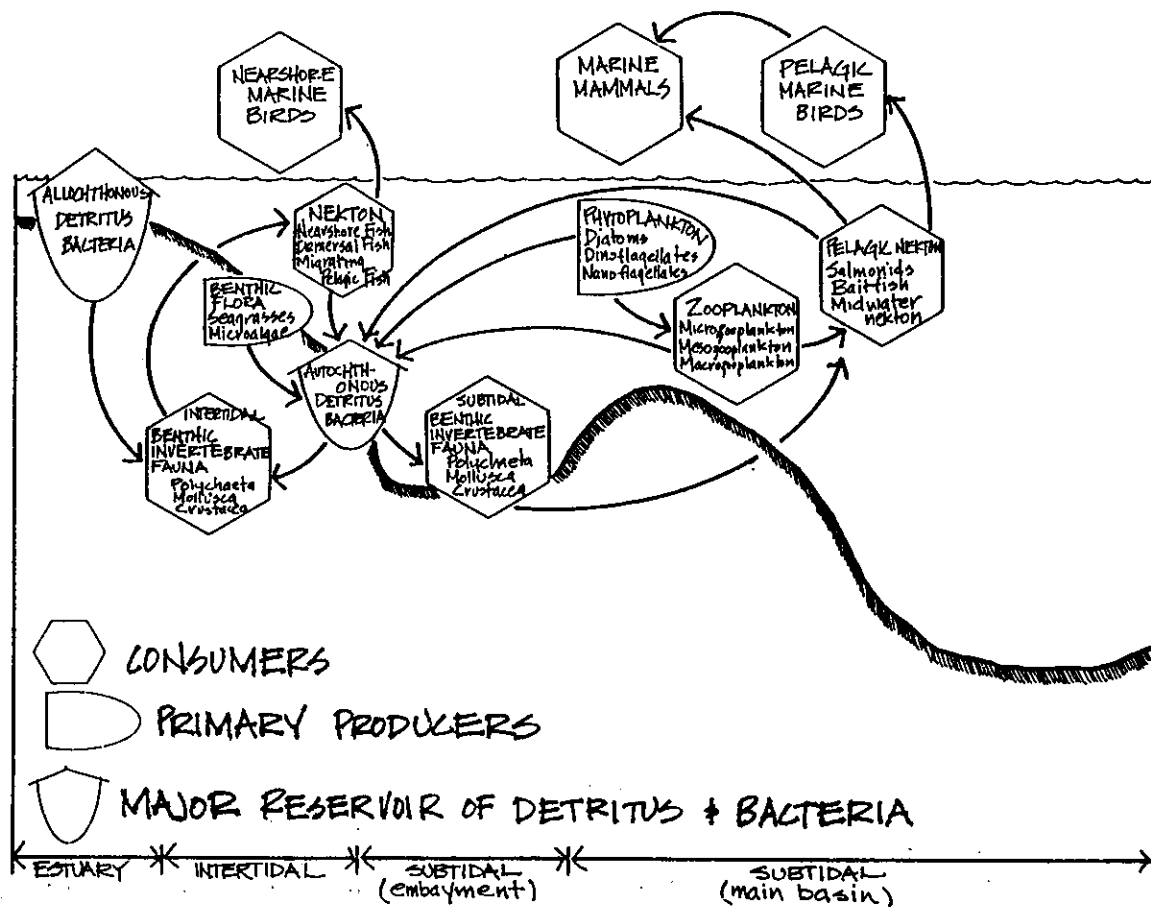
Figure VII-1. Generalized Food Web of Puget Sound. Based on synthesis of
literature sources reviewed for this document.

(Takahashi and Hoskins, 1978). The importance of these organisms for energy flow may be underestimated by measurements of their biomass, since they have higher metabolic rates than larger organisms.

The generalized composition of a detritus particle is shown in Figure VII-2. Kistritz (1978) described the composition of a detritus particle as, "a dead plant particle with its absorbed dissolved organic matter and attendant microflora." In pelagic areas, detritus can originate from several sources: phytoplankton, zooplankton, bacterial decomposition of organic matter, or excretions or secretions from benthic fauna. In nearshore areas, floral components, notably kelp, are an important source of detrital carbon (Simenstad et al., 1979). River discharge and shoreline erosion may also contribute significant amounts of detrital carbon to the system. However, quantitative estimates of the relative contribution of detrital sources to Puget Sound do not exist; nor is information on the spatial and temporal distribution of detritus in relation to Puget Sound's food web. Processes such as detrital degradation, export and utilization are not documented for Puget Sound. Kistritz (1978) discussed these topics for a nearby area, the Fraser River Estuary, using literature from primary sources outside the Pacific Northwest.

The actual food web relationships are more complex than depicted in Figure VII-1. One would only have to look at the diagrams of Simenstad et al. (1979), Wingert et al. (1979), and Chapman et al. (1979) to see the complexity of these relationships. Summarized in matrix form, Tables VII-1 and VII-2 provide documentation of major identified predator/prey relationships of zooplankton and fish in Puget Sound and associated areas.

Many detritivorus fauna, including particular taxa of the polychaeta, gammaridea, and bivalvia, provide the food source of demersal fish sampled as target species by Malins et al., 1980 (Table VII-2). The trace organic compounds and trace metals found in elevated concentrations in the fine sediments of urbanized embayments are consumed by the benthic detritivores and may be transferred to upper trophic levels in the nearshore and demersal food web. To date, no specific studies have documented this transfer of toxicants through the food webs of Puget Sound.

One factor in the predator/prey relationship that may explain the wide prey spectra observed for many species is that many organisms are largely opportunistic feeders. The predators eat the food that is available. A specific example of this phenomenon can be cited for the pile perch. Pile perch and other fish have had their prey identified quantitatively through the use of an index, the IRI (Index of Relative Importance, see Fresh et al., 1979). Pile perch collected near Guemes Island and Cherry Point (north of Whidbey Island) consumed valviferan isopods (73.1 percent of the total IRI), bivalves (10.5 percent), crabs
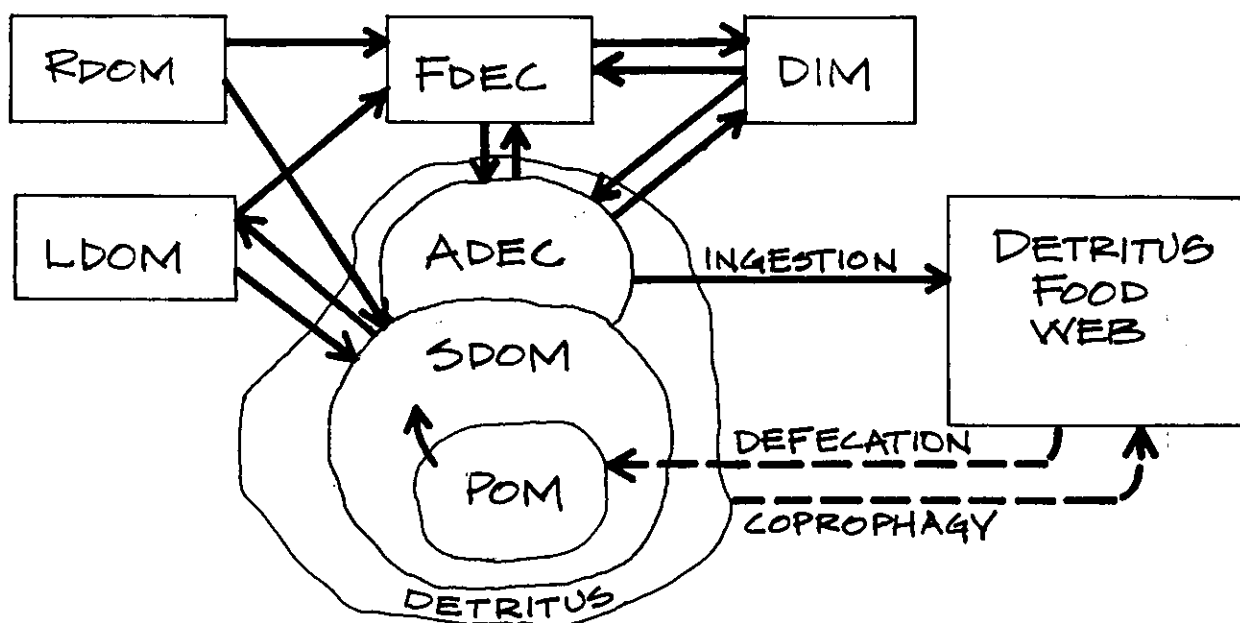
PoM	Particulate Organic Matter
SDOM	Sorbed DOM
ADEC	Attatched Decomposer
LDOM	Labile DOM
RDOM	Refractory DOM
DIM	Dissolved Inorganic Matter
DOM	Dissolved Organic Matter
FDEC	Free Decomposers

Figure VII-2. Conceptual Model of Microbe-Detritus Complex Showing its Biochemical Role and Interconnections with the Detritus Food Web.

Source: Kistritz, 1978 as modified from Clesceri et al., 1977.

TABLE VII-1
FOOD WEB RELATIONSHIPS FOR
COMMON PUGET SOUND ZOOPLANKTON

MICROZOOPLANKTON Predator	Prey Detritus	Nanoflagellates	Diatoms Dinoflagellates	Copepoda
Ciliates	a,c	a,b, c,d	d,e, f	
Flagellates	a,g			
Noctiluca		h	h	i,j
Rotifers	h	h,q		c
Crustacea Larvae	a	k,l, o,p,	m,n	

MESOZOOPLANKTON (Herbivorous) Predator	Prey Detritus	Nanoflagellates	Diatoms	Dinoflagellates
Copepoda Pseudocalanus	r	d,r,t	d,r;s,u, v,w,A	
Calanus			s,u,w,x, y,z,A	
Acartia			m,B,C,D, E	
Paracalanus		t	t,F	F
Urochordata	a	a,G,H,I, J		
Crustacea Larvae Amphipoda		K	K	
Euphausiacea			s,w,kk	
Brachyura		O	O	
Echinodermata Larvae		d,M	K,N	
Annelida Larvae			c,S	

TABLE VII-1 (CONT'D)

MESOZOOPLANKTON (Carnivorous) Predator	Prey	Protozoa	Larvae	Small Copepoda	Large Copepoda	Ctenophora
Chaetognatha		c,d		r,T,U,V	x,T	
Ctenophora			V,Z	Z	r,t,X,Z V,k,Y	V,Z
Cnidaria				r,z,aa, bb	x,aa,bb	
Copepoda Aetidius			cc		.	
Corycaeus				K		
Tortanus		dd	1,dd	K,dd,ee	x	
Euchaeta				K,dd,ff	dd,ff	
Candacia				K		
Acartia			gg			
Calanus			hh			
Crustacea Larvae. Amphipoda			K			
Brachyura			P,Q,R			
Mollusca				ii		

MICRONEKTON Predator	Prey	Detritus	Diatoms	Larvae	Copepoda	Micronekton
Euphausidacea		ii	s,w,jj, kk,ll			
Mysidacea		mm	mm,nn	mm,nn	nn	
Amphipoda					k	
Decapoda						ll

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TABLE VII-1

FOOD WEB REFERENCES

a. King et al. (1980)
b. Fenchel (1980)
c. Chester (1978)
d. Blackbourn (1974)
e. Eddy (1925)
f. Shackleford (1925)
g. Lighthart (1969)
h. Dewey (1976)
i. Kimor (1979)
j. Sekiguchi and Kato (1976)
k. Sonntag and Greve (1977)
l. Ambler and Frost (1974)
m. LeBrasseur et al. (1969)
n. Fernandez (1979a and b)
o. Allan et al. (1977)
p. Poulet (1977)
q. Strathmann et al. (1972)
r. Corkett and McLaren (1978)
s. Parsons et al. (1967)
t. Eppley et al. (1978)
u. Frost (1972)
v. Parsons et al. (1977)
w. Parsons and LeBrasseur (1970)
x. Marshall and Orr (1972)
y. Frost (1977)
z. Runge (1980)
A. Vidal (1978)
B. Landry (1978)
C. Donaghay and Small (1979)
D. O'Connors et al. (1976)
E. Rosenberg (1980)
F. Checkley (1980)
G. Galt (1972)
H. Alldredge (1976)
I. Harbison and McAlister (1979)
J. Pomeroy and Deibel (1980)
K. Dagg (1975)
L. Wilson (1980)
M. Strathmann (1971)
N. Johnson (1931)
O. Gonor and Gonor (1973a and b)
P. Coffin (1958)
Q. Forss and Coffin (1960)
R. Nyblade (1974)
S. Guberlet (1934)
T. Sullivan (1980)
U. King (1979)
V. Sonntag and Parsons (1979)
W. Reeve and Walter (1978)
X. Reeve et al. (1978)
Y. Greve and Parsons (1977)
Z. Arai and Brinckmann-Voss (1980)

aa. Arai and Jacobs (1980)
bb. Huntley and Hobson (1978)
cc. Robertson and Frost (1977)
dd. Johnson (1934a)
ee. Mullin (1979)
ff. Bamstedt and Holt (1979)
gg. Lonsdale et al. (1979)
hh. Landry (1980)
ii. Conover and Lalli (1974)
jj. Mauchline and Fisher (1969)
kk. Ross (1979)
ll. Cooney (1971)
mm. Thorne (1968)
nn. Siegfried and Kopache (1980)
oo. Fresh et al. (1979)
pp. Kaczynski et al. (1973)
qq. Simenstad et al. (1979)
rr. DOE (1977)
ss. Gallagher (1979)
tt. Fresh and Cardwell (1979)
uu. Feller and Kaczynski (1975)
vv. Sibert et al. (1977)
ww. LeBrasseur (1969)
xx. Kirkness (1948)
yy. Moring (1973)
zz. Peterman and Gatto (1978)
AA. Parametrix (1976)
BB. Maynard (1972)
CC. Arthur (1977)
DD. Scura and Jerde (1977)
EE. Hueckel (1980)
FF. Miller et al. (1978)
GG. Wingert et al. (1979)
HH. Jones and Geen (1977)
II. Koeller et al. (1977)

Footnotes:
1 For complete taxonomic coverage, most references are from outside of
  Puget Sound.

TABLE VII-2

FOOD WEB RELATIONSHIPS FOR
COMMON PUGET SOUND FISH

SALMONIDS Predator \ Prey	Epibenthos	Larvae	Copepoda	Calanoida	Harpacticoida	Gammaridea	Eucarida Decapoda	Euphausiacea	Micronekton (fish eggs)	Ostracods/ Urochordata	Insecta	Fish Larvae	Fish Juvenile	Bait Fish
Pink Larvae	oo,pp qq	M,qq	M,w, oo,qq						qq	qq				
Pink Juvenile	oo	pp	W,oo pp,qq	,oo					pp,w rr,ss	rr,qq ,oo		rr		
Pink Adult	rr	tt	rr						rr,tt			rr		
Chum Larvae	oo,qq ww,tt vv		tt,rr ww,m, w											
Chum Juvenile	oo,tt		Y,v,ll oo,qq tt,ww		■,oo	□,oo			V,oo tt,qq rr	qq				
Chum Adult	rr			rr					rr					
Chinook Juvenile	oo,tt qq	oo,tt qq,rr	oo,tt qq				□,oo		oo,tt xx	qq	oo,tt qq,rr	tt,qq rr		oo,tt rr,yy
Chinook Adult									xx					
Coho Juvenile	oo,tt qq,rr	oo,tt qq,rr	tt,qq				□,oo		oo,tt qq	oo	oo,qq rr,tt	pp,zz oo,tt rr,qq		qq,rr
Coho Adult	tt,xx	tt,xx							rr,xx AA			oo,tt xx		rr,xx
Sockeye Juvenile	qq	qq	qq,rr				O,qq	O,qq	qq,rr					qq,rr
Sockeye Adult				rr					rr					rr
Steelhead Juvenile	oo,rr		rr						rr			rr	zz	oo
Steelhead Adult	rr		tt			,oo			tt	tt	tt	,oo	rr	oo,rr
Cutthroat Adult	oo,tt rr					,oo			oo	□,oo	rr	rr,tt	rr,tt	rr,tt

■,IRI = 76-100%
▲,IRI = 51-75%
○,IRI = 26-50%
□,IRI = 10-25%

TABLE VII-2 CONTINUED

MIDWATER NEKTON Predator / Prey	Epibenthos	Detritus	Eggs & Larvae	Copepoda	Calanoida	Gammaridea	Bivalvia	Micronekton	Caridea	Cephalopoda (Squid, Octopus)	Cestoda	Larvae & Juvenile Fish	Bait Fish
Shrimp	rr	rr		rr				rr				EE	
Cod Juvenile			tt	oo,rr				oo					
Cod Adult	rr		rr	qq				FF	rr,FF			tt,rr FF	tt,rr
Tomcod Juvenile	qq					O,GG							
Tomcod Adult	rr,tt GG			rr,GG		O,GG							
Hake Juvenile				rr				rr	rr			rr,tt	
Hake Adult													rr,tt BB
Pollock Juvenile	qq		qq,rr	qq,rr				qq					
Pollock Adult	BB		HH		■,qq			rr,tt BB	rr,BB	rr,BB		rr,BB	rr,tt BB
Dogfish	oo,qq BB							rr,BB	rr,AA BB	rr,BB		oo,rr yy,BB	qq,BB HH
Ratfish	qq,rr GG						O,GG	oo,rr yy,BB	rr,HH		O,GG	oo,rr GG	
Midshipman			rr					rr,BB	rr			rr	
Sablefish								rr				rr	rr

■, IRI = 76-100%
▲, IRI = 51-75%
O, IRI = 26-50%
□, IRI = 10-25%

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TABLE VII-2 CONTINUED

BAITFISH / Predator	Phytoplankton	Protozoa	Epibenthos	Larvae & Eggs	Copepoda	Calanoida	Harpacticoida	Cumacea	Gammaridea	Mysidacea	Decapoda	Flarellifera	Larvacea Cladocera Ostracods	Micronekton	Fish Larvae
Herring															
Larvae	rr,BB			r,m,rr tt,BB	r,m,B oo,tt, rr,BB								oo,rr	rr,qq tt	oo,qq
Juvenile			oo	m,qq, rr	qq,tt	■,qq	□,qq						BB	tt,qq rr,BB	qq,rr
Adult		DD	qq												
Sardine & Anchovy															
Juvenile	DD		qq	CC	qq,rr						□,qq		□,qq	rr	rr
Adult			qq	qq,rr		□,qq	□,qq								
Sand Lance															
Juvenile	rr		rr	m,rr	■,rr	■,qq									rr
Adult			qq,rr tt	■	r,qq rr,tt									rr	qq,rr
Surf Smelt			qq,rr	oo,rr	B,oo qq,rr tt	□,qq		□,qq		□,qq		□,qq	qq,tt		
Longfin Smelt			qq	qq	qq,rr				■,qq					qq,rr	
Miscellaneous															
Larvae		c,d,h			■								~		
Juvenile				■	■										

■,IRI = 76–100%
▲,IRI = 51–75%
O,IRI = 26–50%
□,IRI = 10–25%

TABLE VII-2 (CONTINUED)

REFERENCES

a. King et al. (1980)
c. Chester (1978)
d. Blackbourn (1974)
h. Dewey (1976)
m. LeBrasseur et al. (1969)
r. Corkett and McLaren (1978)
w. Parsons and LeBrasseur (1970)

oo. Fresh et al. (1979)
pp. Kaczynski et al. (1973)
qq. Simenstad et al. (1979)
rr. WDOE (1977)
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tt. Fresh and Cardwell (1979)
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vv. Sibert et al. (1977)
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xx. Kirkness (1948)
yy. Moring (1973)
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B. Landry (1978)
M. Strathmann (1971)
V. Sonntag and Parsons (1979)
W. Reeve and Walter (1978)
Y. Greve and Parsons (1977)

AA. Parametrix (1976)
BB. Maynard (1972)
CC. Arthur (1977)
DD. Scura and Jerde (1977)
EE. Hueckel (1980)
FF. Miller et al. (1978)
GG. Wingert et al. (1979)
HH. Jones and Geen (1977)
II. Koeller et al. (1977)

Footnotes:

1 For complete taxonomic coverage, most references are from outside of Puget Sound.

(9.7 percent), and gammarid amphipods (4.5 percent), while the same species collected in the Strait of Juan de Fuca consumed gastropods (32.1 percent), pagurid crabs (22.6 percent), gammarid amphipods (13.6 percent), brachyuran crabs (11.5 percent), sphaeromatid isopods (2.6 percent), valviferan isopods (5.9 percent), and tanaids (2.8 percent).

At one place and time, a large spectrum of biota may be present, but generally there will be one or a few components at each trophic level whose abundance and/or biomass are at maximum levels. Such a maximum in standing stock allows predators to most readily utilize this food source (i.e., maximum prey consumed per effort). As discussed in previous sections, these maximum levels change in time and space as populations grow and/or migrate. Physical driving forces alter these maximum; diatom blooms, for example, are stimulated by long retention time and moderate stratification. Biological and chemical mechanisms also change the maxima through: 1) competition and predation, 2) reproductive stimulation by adequate food supply, and 3) decomposition and recycling of matter and energy via detritus and dissolved organic carbon, into bacteria and other small particles (Sheldon et al., 1967; Johnson and Cooke, 1980). The consequences of these interactions are as yet poorly understood; examples are provided by Parsons and LeBrasseur (1970) and Huntley and Hobson (1978). A theoretical treatment is given by Silvert and Platt (1978).

At the same time, what prey each predator specifically utilizes is controlled by several factors. One of these is a strong trend for correlation between body sizes of prey and predators. An example of this relationship is shown for pelagic biota in Figure VII-3. It indicates that animals of a similar size generally select prey from within a similar range of sizes, measured in this case as body length. Thus pelagic biota in Figure VII-3 are grouped by size classes rather than by taxonomic groups. The size correlation exists for different life stages of a single species, as well as for different species and phyla. Maturation and growth of animals is a major agent of energy and biomass flow between the trophic size classes.

There are exceptions to the general predator-prey size trend. They include: 1) predator selectivity (e.g., documented for juvenile chinook salmon's selectivity for terrestrial insects), 2) predator feeding structure morphology (e.g., polychaete variability as shown by filter feeders, deposit feeders, and carnivores, all of similar size), and 3) predator life cycles (e.g., ctenophores and medusae are usually unavailable as prey during the winter due to their life cycle).

Benthic invertebrate fauna have been categorized according to their feeding modes by Malins et al. (1980), Thom et al. (1979), Dexter et al. (1979), and Fauchald and Jumars (1979). The main feeding mode divisions have been characterized as: 1) suspension or filter feeders, 2) surface
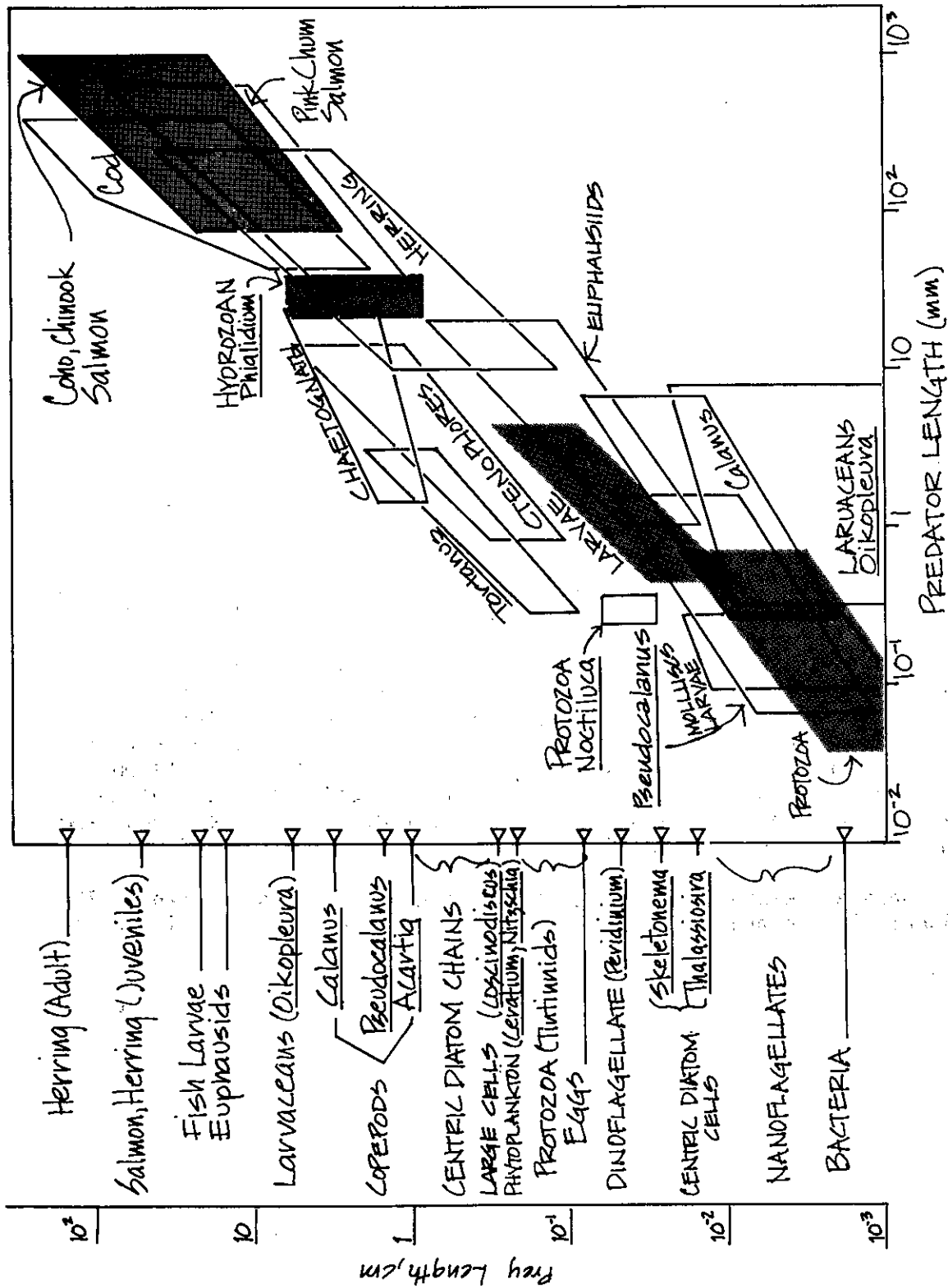
Figure VII-3. General Correlation Between Sizes of Prey and Predator. Based on synthesis of literature sources reviewed for this document.

deposit feeders, 3) sub-surface deposit feeders, 4) carnivores, and 5) herbivores. The suspension or filter feeders consume the suspended particulate matter in the water column whereas the deposit feeders directly consume deposited particulate matter. The deposited fine particulate matter tends to concentrate trace organic compounds and trace metals. This suggests that the detritivorus food web may experience more rapid biomagnification of toxicants than a planktivorus food web. Feeding modes for select polychaetes are shown in Table VII-3.

Within the plankton, many species are recognized as selective size feeders. Microzooplankters feed on detritus, bacteria, and nanoflagellate phytoplankton. Larvae, both holoplanktonic and meroplanktonic, change their prey size as they grow. Herbivorous net plankton and micronekton use their appendages primarily as filters to capture phytoplankton. At the same time, carnivorous zooplankton use their appendages for grasping and hence may have a more restricted prey spectrum. Some herbivores, however, are facultative carnivores (i.e., Calanus, Landry, 1980; Euphausia, Parsons and LeBrasseur, 1970).

The diets of salmon species have been well defined for Puget Sound and illustrate size dependence and dependence on spatial and temporal fluctuations in availability of prey. Pink and chum salmon begin feeding in estuaries on epibenthic prey, including harpacticoid copepods and gammarid amphipods (Fresh et al., 1979; Fresh and Cardwell, 1979; Feller and Kaczynski, 1975). When they reach a length of 50 to 60 mm, they move offshore and shift to pelagic prey such as calanoid copepods, larvaceans, and metazoan larvae. Gallagher (1979) found some competition for food between pinks and chums when both are present. Pinks and chums, in turn, fall prey to juvenile coho, steelhead, and sculpin (Peterman and Gatto, 1978).

The larger juvenile chinook and coho have a larger and more diverse prey spectrum, evolving with age from invertebrate plankton and epibenthos and progressing to juvenile fishes. The prey spectrum includes riverborne insects, mysids, cumaceans, and shrimps, in addition to copepods and larvae while nearshore; euphausiids, ostracods, isopods, crab larvae and sand lance are taken further offshore (Fresh et al., 1979; Fresh and Cardwell, 1979). Juvenile chinook and coho fall prey to larger fishes, including silvers, blackmouths, and cutthroat. Oldest and largest upon reaching saltwater are sockeye, steelhead, and cutthroat, which subsist on crustaceans and insects, baitfishes, and juveniles of salmon and nearshore and bottomfish (rockfish, flatfish, perch, sculpin) (WDOE, 1977).

The major prey of select nearshore and demersal fish have also been shown in Table VII-2. As expected, the prey spectra of many fish species differ from one habitat to another.

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TABLE VII-3

POSSIBLE FEEDING GUILD CHARACTERISTICS OF THE MOST ABUNDANT POLYCHAETE
FAMILIES FOUND IN ELLIOTT BAY

PREDATOR/FEEDING GUILD CATEGORY	Herbivore	Carnivore	Subsurface Deposit Feeder	Surface Deposit Feeder	Facultative Deposit Feeder	Motile	Sessile	Jawed	Tentaculae	Other Structures
Capitellidae			X	X		X				X
Maldanidae			X				X			X
Paraonidae	X			X		X				X
Cossuridae			X			X				X
Lumbrineridae			X			X		X		
Spionidae				X		X			X	
Cirratulidae				X		X			X	
Glyceridae		X			X	X		X		
Nephtyidae		X			X	X		X		
Ampharetidae				X		X	X		X	
Syllidae		X				X		X		
Spionidae				X			X		X	
Nephtyidae		X			X	X				

References:

X Fauchald and Jumars (1979)

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Predator/prey relationships of the birds utilizing Puget Sound are not well documented from a quantitative viewpoint. Information in Table VII-4 shows that several families have picivorous habits. Molluscs and crustaceans are also common prey to several species.

All Puget Sound mammals feed on a wide variety of pelagic and demersal fishes (Table VII-5). Benthic organisms are included in the diets of the otter, the seals, and sometimes the gray whale. The baleen whales (gray, humpback, minke) also eat significant quantities of plankton down to the size of copepods. Killer whales, assumed to eat large quantities of other mammals, may eat more fish in Puget Sound, where the mammal stocks may be insufficient to support them (Simenstad et al., 1979).

Using the concept of predator prey size correlation, the pelagic portion of the generalized food web of Figure VII-1 can be expanded and described as one of two parallel chains based on diatoms or nanoflagellates (Figure VII-4).

Greve and Parsons (1977) presented this model and postulate that a switching from large to small phytoplankton reduces the trophic energy available to commercial fishes, for two reasons: 1) it increases the number of trophic levels and thus decreases overall transfer efficiency; and 2) it channels energy flow into gelatinous zooplankton, a trophic dead end, rather than into fish. Their hypothesis rests on the observed predominance of the nanoflagellate-based food chain in experimental enclosures, particularly under pollutant stress and weak vertical mixing.

If valid, this model could reveal profound consequences for the survival of larval and juvenile fishes, which are believed to suffer mortality if appropriate food is not available (Peterman, 1978; Walters et al., 1978; Lasker, 1975; Scura and Jerde, 1977; Werner and Blaxter, 1980). At present, it has not been possible to test the hypothesis either in the field or experimentally (Grice et al., 1980).

Figure VII-5 provides a synthesis of the Puget Sound food web which demonstrates the predator-prey size relationships. Strong trophic energy flows are indicated by the bold lines. There are important mechanisms by which trophic energy is transported into, within, and out of the food web:

a) Detritus from terrestrial habitats is imported by river discharge, especially during high seasonal runoff. Shoreline erosion also may contribute a substantial input to the detrital pool.

b) Autotrophic production in the form of benthic flora and phytoplankton provides both a direct food source and also contributes substantially to the detrital pool. Circulation affects the distribution of plankton and nutrients, creating an energy flux into, within, and out of Puget Sound.

TABLE VII-4

BIRD PREY SPECTRA

	Fish	Fish eggs	Small animals	Frogs	Molluscs	Crustacean	Insects	Insect larvae	Polychaetes	Eelgrass	Saltmarsh plants	Grains (rice)	Seeds	Sedge
NEARSHORE														
Shorebirds														
Ardeidae	JJ		JJ	JJ										
Charadriidae					qq	qq	qq							
Scolopacidae					qq	qq	qq	qq	qq					
Phalaropodidae														
Casual Marine Feeders														
Accipitridae	qq													
Pandionidae	qq													
Alcedinidae	qq													
PELAGIC														
Gaviidae	qq	qq			qq	qq								
Podicipedidae	qq					qq								
Phalacrocoracidae	qq				qq	qq								
Anatidae	qq				qq				qq	qq	qq	qq	qq	qq
Stercorariidae	qq				qq		qq							
Laridae	qq	qq			qq	qq								
Alcidae	qq					qq								

References:

JJ   Salo (1975)
qq   Simenstad et al. (1979)

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TABLE VII-5

MAMMALS PREY SPECTRA

MAMMALS

Predator/Prey	Copepods Euphasids	Benthos	Nearshore Fishes	Demersal Fishes	Salmon	Bait fish	Midwater Nekton	Mammals
River Otter		KK,NN	KK,NN	KK,NN	KK,NN			
California Sea Lion				KK	KK		KK,LL,qq	
Steller's Sea Lion				KK	KK	KK	KK,LL,qq	
Harbor Seal			MM			KK	KK,MM,	
Elephant Seal		KK,LL,qq		KK,L,qq			KK,LL,qq	
Killer Whale	KK,LL,qq,00	KK,LL,qq,00				KK,LL,qq,00		
Minke Whale	KK					KK,LL	KK	
Humpback Whale	KK,00					KK,rr		
Harbor Porpoise						KK,LL,qq	LL,qq	
Dall's Porpoise				KK		KK,LL,qq	KK,LL,qq	
White-sided Dolphin					KK	KK,LL,qq	KK,LL,qq	

References:
KK - Everitt et al. (1979 and 1980)
NN - Harris (1968)
LL - Balcomb and Angell (In press)

MM - Calambokidis et al. (1978)
qq - Simenstad et al. (1979)
00 - Haley (1978)
rr - DOE (1977)

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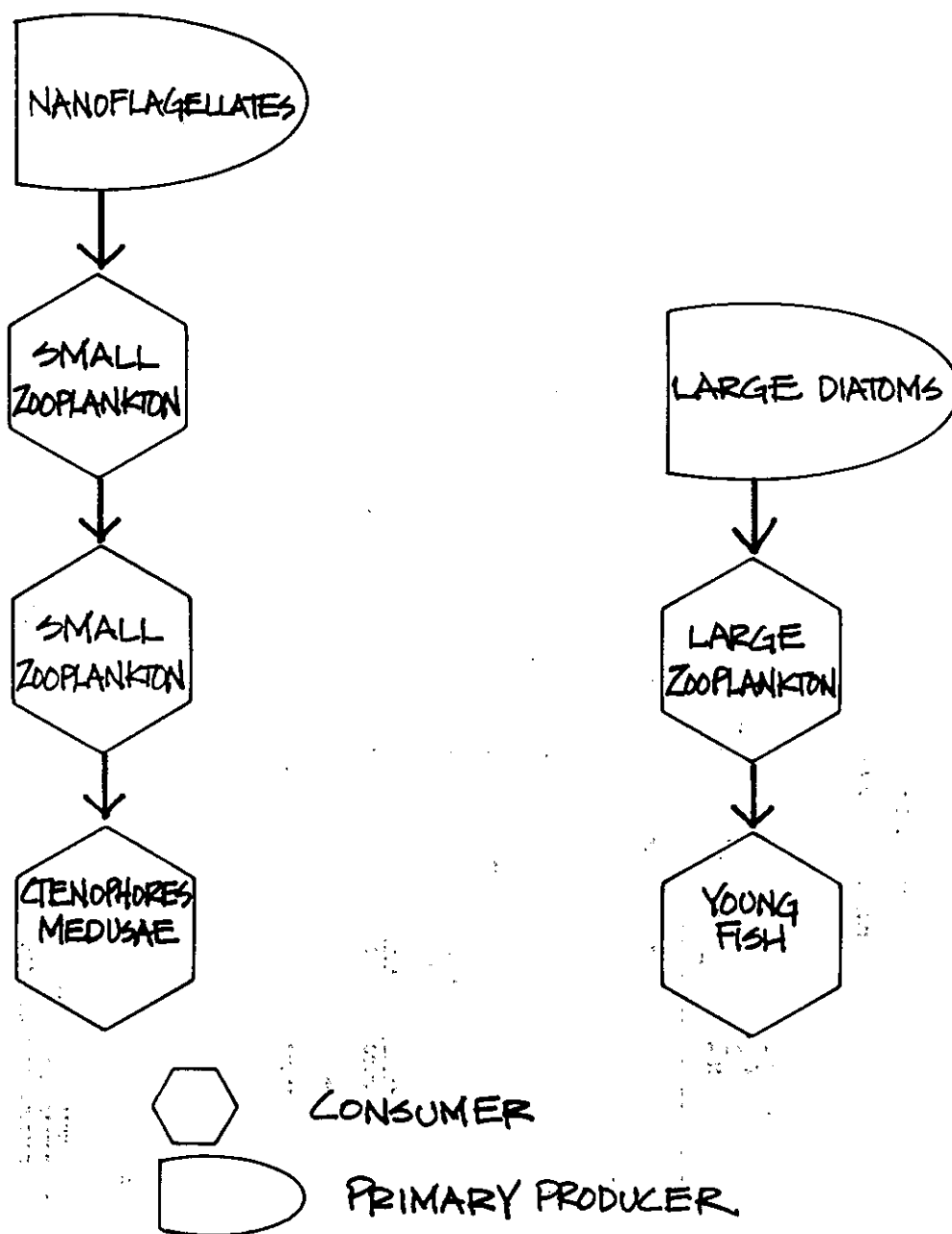
Figure VII-4. Parallel Food Chains Based on Plankton Size.

Source: Greve and Parsons, 1977.

Symbol		
⬡	CONSUMER	
⬗	PRIMARY PRODUCER	
⬔	MAJOR RESERVOIR	
→	MINOR TROPHIC ENERGY PATHWAY	
┈┈>	MAJOR TROPHIC ENERGY PATHWAY	
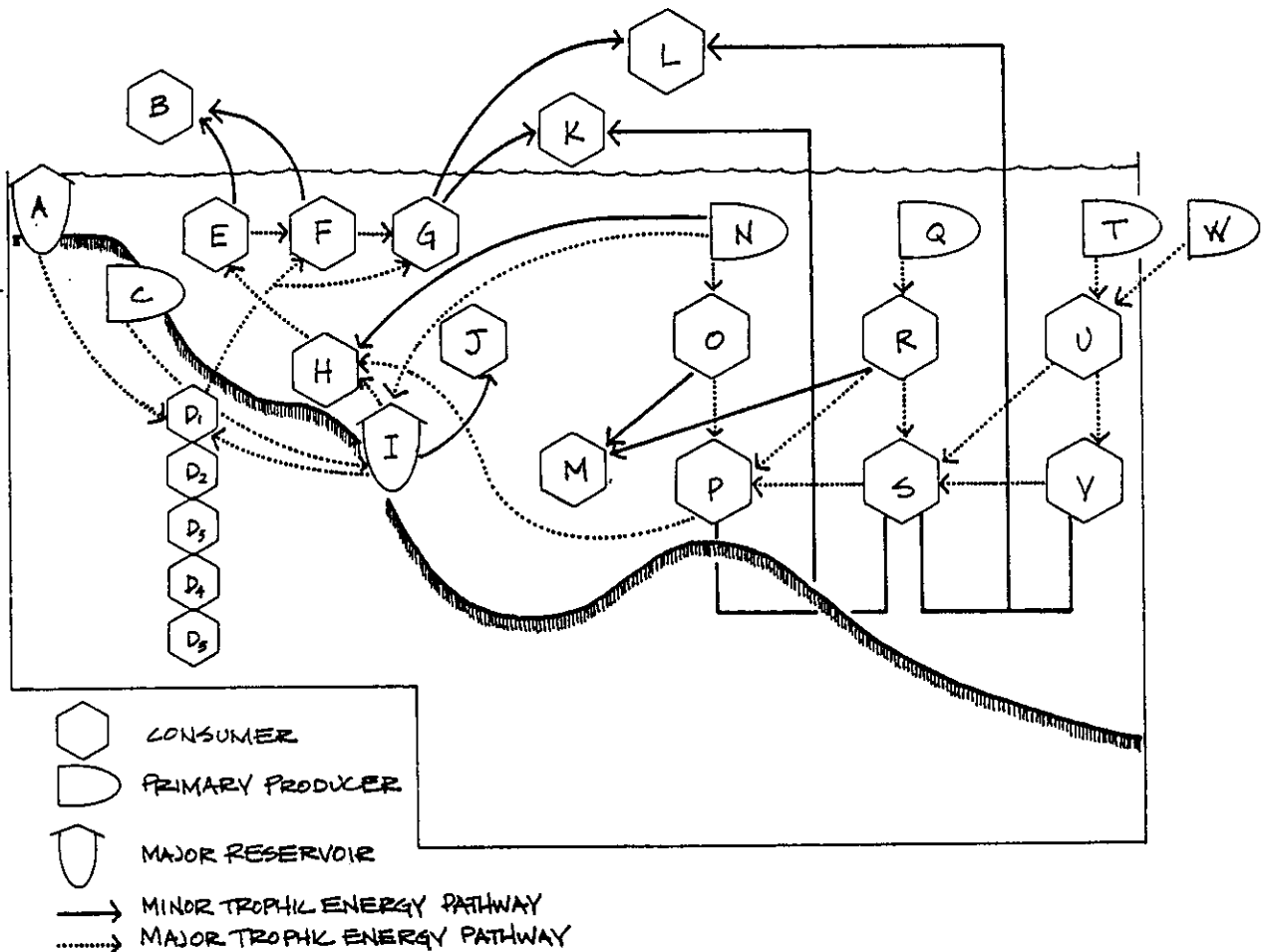
A. DETRITUS/BACTERIA (Fig. VII-2)

B. NEARSHORE MARINE BIRDS

C. BENTHIC FLORA
   Seagrasses
   Macroalgae

D₁ BENTHIC INFAUNA
   Suspension or Filter Feeders

D₂ BENTHIC INFAUNA
   Surface Deposit Feeders

D₃ BENTHIC INFAUNA
   Subsurface Deposit Feeders

D₄ BENTHIC INFAUNA
   Herbivores

D₅ BENTHIC INFAUNA
   Carnivores

E. LARVAL "BENTHIC" FISH

F. JUVENILE "BENTHIC" FISH

G. ADULT "BENTHIC" FISH

H. EPIBENTHIC ZOOPLANKTON

I. DETRITUS/BACTERIA

J. MICROZOOPLANKTON
   100μ - 100 mm
   protozoa
   nauplii

K. MARINE MAMMALS

L. PELAGIC MARINE BIRDS

M. PLANKTONIC CARNIVORES
   3-120 mm
   Chaetognaths, Ctenophores
   Medusae, Amphipods, Mysids
   Copepods

N. NANOFLAGELLATES
   3-20μ

O. SMALL NET ZOOPLANKTON
   1-5 mm
   Small Copepods, Copepodites
   Mollusk veligers.

P. LARVAL FISH
   10-50 mm
   Pink and Chum salmon
   Herring and Baitfish
   Midwater

Q. SMALL DIATOMS
   20-100μ

R. LARGE NET ZOOPLANKTON
   5-10 mm
   Large Copepods
   Crustacean Larvae
   Echinoderm Larvae
   Annelid Larvae

S. JUVENILE FISH
   50-200 mm
   all salmon midwater
   adult baitfish, adult shrimp

T. LARGE DIATOMS
   100-500μ

U. MICRONEKTON
   10-20 mm
   Euphausiids
   Mysids

V. ADULT FISH
   >200 mm
   salmon midwater

W. DINOFLAGELLATES
   50-300μ

Figure VII-5. Puget Sound Food Web with Predator/Prey Size Relationships. Based on synthesis of literature sources reviewed for this document.

c) The horizontal migration of fishes, particularly salmon and herring, between estuaries and embayments, the open Sound and the Pacific, transports energy into and out of the food web. Energy is exported in the spring during emigration, and imported during fall and winter during immigration. Data are not available to determine whether the net import/export balance is positive or negative.

d) The vertical migrations of zooplankton and fish, both seasonal and diel, cycle energy within the system. Energy is imported to the euphotic zone in the spring during spawning, and exported to deeper water and sediments during the rest of the year. Animals feed near the surface, but defecate at depth; in addition, there is a tendency for animals to be prey for a successively deeper-living predator. This, in most cases, exports more trophic energy to the sediments than does direct sinking of organisms (Shuman, 1978).

e) In addition, there is energy transported within the system by the seasonal appearance in the water column of meroplanktonic larval, and a net export when larvae later settle.

f) Nearshore, energy from epibenthic organisms is transferred to young fish. In addition, suspended matter and small plankton are consumed by benthic filter-feeders. Some data are now becoming available to evaluate this transfer (Naiman and Sibert, 1979).

There are differences between the food webs of the Main Basin, of deep embayments such as Elliott and Commencement Bays, and of shallower and more protected embayments such as Budd and Sinclair Inlets.

The Southern Sound and Sinclair Inlet have a large littoral zone and are relatively shallow; they thus exclude much of the larger end of the size spectrum of biota, but correspondingly become very important in spring during the season of inshore phytoplankton blooms and presence of larvae. Particularly important as nursery grounds for smaller fishes are the estuary zones at river mouths in the Southern Sound (e.g., Fresh et al., 1979).

Elliott and Commencement Bays are less important as nursery grounds being less protected and having less littoral zone area. They are more closely linked to the open-water habitat of the Main Basin, which serves as summer feeding grounds for the larger portion of the pelagic size spectrum. The estuary zones at the mouths of the Duwamish and Puyallup Rivers are important spring nursery grounds for baitfish and salmon.

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CHAPTER 8. TRACE METALS

Trace metals are ubiquitous constituents of the environment. They are natural components of soils and sediments and most are required nutrients for biological organisms. As implied in their nomenclature, however, these elements normally occur only at very low levels in natural matrices, i.e., parts per million (ppm) or less. At higher concentrations, many are toxic as indicated by the use of arsenic (As), copper (Cu), and lead (Pb) compounds as insecticides. Hence, environmental problems associated with trace metals result when the concentrations are in excess of natural levels. Due to their widespread usage in commerce, the opportunities for contamination of the environment are many.

Within Puget Sound, the concentrations and distributions of a number of trace metals have been examined. This chapter summarizes these data, examining principally those metals which may be causing toxicological problems due to high concentrations.

OVERVIEW OF TRACE METALS IN PUGET SOUND

A comparison of the observed elemental composition of the sediments in Puget Sound collected from sites distant from urbanized areas (Table VIII-1) indicates general similarities of the concentrations of elements in the sediments with the levels observed in non-contaminated nearshore sediments from other areas, the composition of Puget Sound regional soils, and with the average composition of the earth's crust. These data indicate that by and large Puget Sound is not contaminated with any trace element.

At the same time, site-specific data, particularly from stations near urbanized areas have shown levels of a number of trace metals much higher than those presented in Table VIII-1. To identify these "problem" metals, a two-step approach was taken. First, this report was limited principally to those elements considered to be toxic to the biota, i.e., those which are included on EPA's list of priority pollutants. This group is comprised of:

Antimony (Sb)	Mercury (Hg)
Arsenic (As)	Nickel (Ni)

TABLE VIII-1

COMPARISONS OF THE ELEMENTAL COMPOSITION
OF PUGET SOUND SEDIMENTS

Element	Concentration, μg/g (unless indicated)			
	Puget Sound "Background" Sediments	Near-Shore Sediments[a]	Puget Sound Regional Soils[b]	Average Earth's Crust[c]
Si	28%[d]		>10%	28%
Al	6.4%[e]		7%	8.1%
Fe	3.6%[e]		3%	5.0%
Ca	3.17%[d]		2.5%	3.6%
K	1.1%[d]		1%	2.6%
Na	2.3%[d]		2%	2.8%
Mg	0.66%[f*]		1.5%	2.1%
Ti	3533[d]		7000	4400
Mn	496[d]		700	1000
Sr	270[d]	<250	200	300
Ba	23.6[f*]	750	500	250
Zr	5[f*]	160	150	220
Cr	101[e]	100	80	200
V	110[d]	130	90	150
Zn	87[f,g]	95	80	132
Ni	42[f,g]	55	80	80
Cu	35[f,g]	48	20	70
W	14[f*]		<10	69
Sn	17[f*]	21	<2	40
Co	12[f]	13	10	23
Y	7[f*]		30	28
Pb	21[f,g]	20	15	16
Mo	7[f*]		<2	15
Ga	16[d]	19	20	15
Be	0.4[f*]		1	6
As	18[e]		<100	5
Sc	5[f*]		18	5
Sb	1.5[e]		<15	1
Hg	0.06[e,f]		- - -	0.5
Cd	3[f,h]		<7	0.15
Ag	1.9[f*]		<0.7	0.1
Se	<1.5[d]		- - -	1.09

[a]Aston and Chester, 1976.

[b]Pevear, D., Geology Department, Western Washington University, unpublished data.

[c]CRC, 1974.

[d]Riley et al., 1980.

[e]Crecelius et al., 1975.

[f]Malins et al., 1980.

[g]Schell et al., 1977.

[h]Cummins et al., 1976.

*The values reported for these elements are based on a limited survey and may not be accurate.

Beryllium (Be)	Selenium (Se)
Cadmium (Cd)	Silver (Ag)
Chromium (Cr)	Zinc (Zn)
Copper (Cu)	Thallium (Tl)
Lead (Pb)	

Secondly, the data for the concentrations of these elements in the surface (0-5 cm) sediments were pooled and examined to determine the presence of regionally elevated levels. The sediment data provide the most coherent description of the long-term integrated distribution of trace element loadings to the Sound, and the greatest number of elements have been measured in this component.

For this evaluation, a subjective criterion was developed for each metal as a reference point for identifying those metals which appear to be present at levels significantly above natural concentrations. This criterion was the mean of the concentrations of that metal observed in non-urbanized "reference" areas plus twice the standard deviation of the mean. This established an approximate confidence interval limit for the natural range of the concentrations to account for natural and analytical variability. Concentrations of the metal which exceeded this limit were considered to be in excess and hence indicative of pollution. On this basis, the toxic metals could be divided into four groups:

1. Selenium and thallium for which no reliable data are currently available.

2. Chromium and nickel for which no concentrations were noted which exceeded the criteria.

3. Silver, beryllium, and cadmium for which the data are limited and of unknown quality but at worst indicate minor regional impacts usually less than twice the criteria level. Silver has been observed in excess in all four urban embayments (Elliott and Commencement Bays, and Budd and Sinclair Inlets), cadmium in Elliott and Commencement Bays and Budd Inlet, and beryllium only in Elliott Bay (Malins et al., 1980; J. Blazevich, U.S. EPA, Region X, unpublished data, 1973).

4. Arsenic, antimony, copper, lead, zinc, and mercury which have been observed at very high concentrations, often greater than an order of magnitude above the reference criteria, in nearly all urban areas.

On the basis of this analysis, it was deemed appropriate to concentrate on the latter group of metals for this chapter since they demonstrate the strongest impact of humankind, and the greatest potential for inducing toxic response in resident organisms and their consumers.

The data summarized below are from a number of sources and were often obtained by different analytical techniques, primarily atomic adsorption spectrophotometry or neutron activation. As a result, it should be recognized that the data may not be entirely comparable among studies. However, an effort was made in preparing this report to rely on data which appeared to be adequately verified by standardization procedures and intercalibrations. Therefore, the data are combined without distinction in the following discussion.

DISTRIBUTION IN SEDIMENTS

As discussed above, the data for trace metals in the sediments constitute the largest number of data points for samples from the Sound. Since the sediments also provide a long-term integrated record of the trace metals' inputs, these data provide the best synoptic characterization of their distribution.

General Distribution

The concentrations of the selected trace metals observed in the surface sediments are summarized in Figure VIII-1, as bar diagrams of the average concentrations for selected sub-regions. In general, the concentrations of the metals are spatially uniform with relatively small increases associated with basins of known urban inputs. The two major exceptions to this generalization are the sediments near the ASARCO Smelter in Commencement Bay and those near the mouth of the Duwamish River. Sinclair Inlet appears to be intermediate in the levels of many trace metals. The latter areas will be discussed in more detail below.

Much of the regional data from the embayments which indicate higher values in urbanized areas tend to be biased for two reasons. First, as is illustrated in the detailed presentation of the data from these areas (Figures VIII-2 through VIII-3), the regional averages tend to be skewed by one or a few values exhibiting very high metals concentrations. Secondly, as discussed in the Sedimentation Chapter, the embayments tend to accumulate comparatively fine-grained sediments which are enriched in trace metals (see discussion below).

Figure VIII-1. Averaged Concentrations of Selected Trace Metals Observed in the Sediments of Puget Sound.

Data from 1) Crecelius et al.,1975: 2) Schell et al., 1977: 3) Malins al., 1980: 4) Cummins et al., 1976: 5) J.N. Blazevich, U.S. EPA Region X, unpublished data, 1973: 6) METRO, 1980; 7) Tomlinson et al., 1976.

LEGEND

SCALE

100 mg/g As, Sb, Cu, Pb, Zn
1 mg/g Hg

2 NUMBER OF SAMPLES
3 SOURCE OF DATA
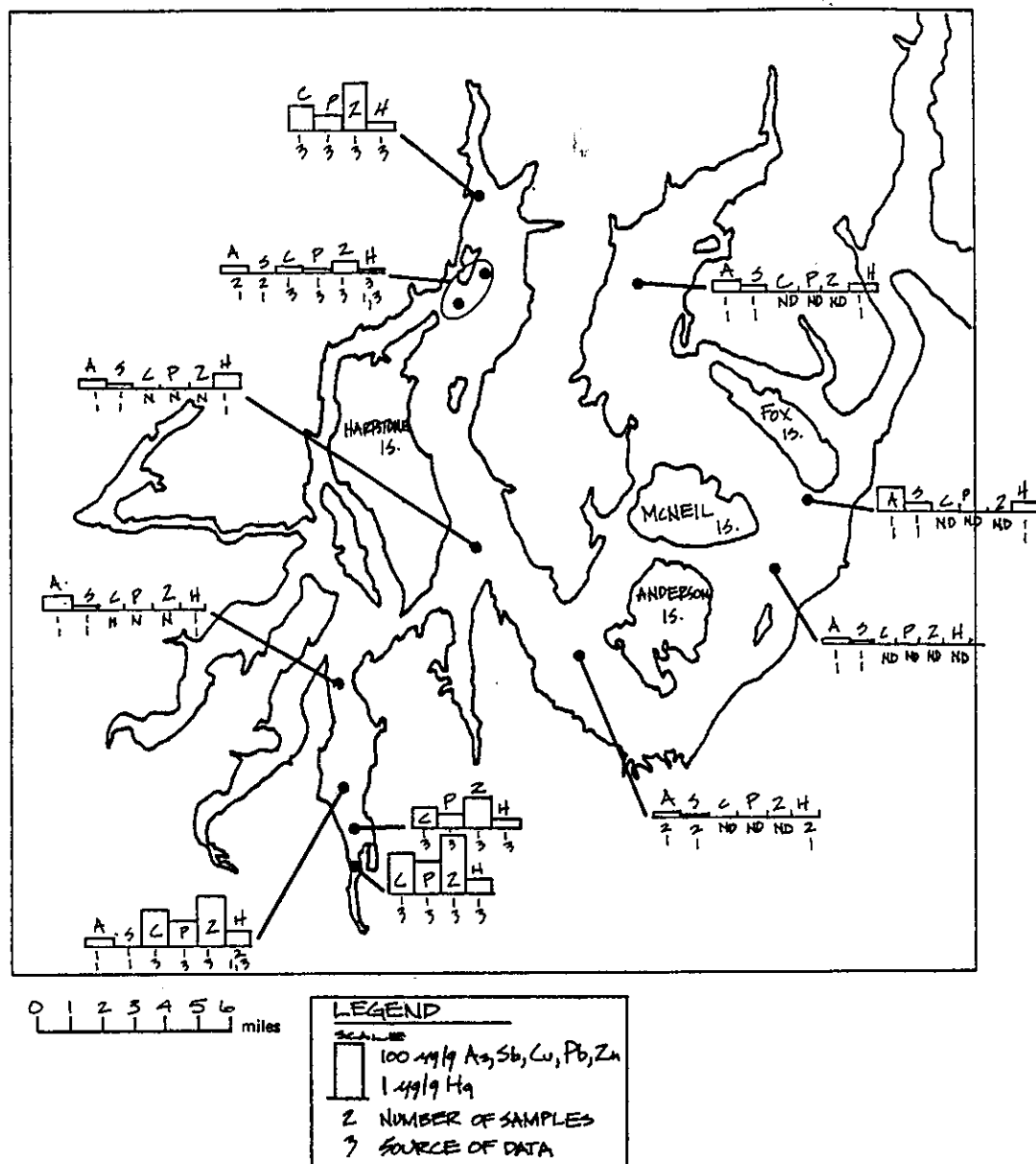
Figure VIII-2.   Concentrations of Selected Trace Metals Observed in the Sediments of Budd Inlet and the Southern Sound.

Data from 1) Crecelius et al., 1975; 3) Malins et al., 1980.
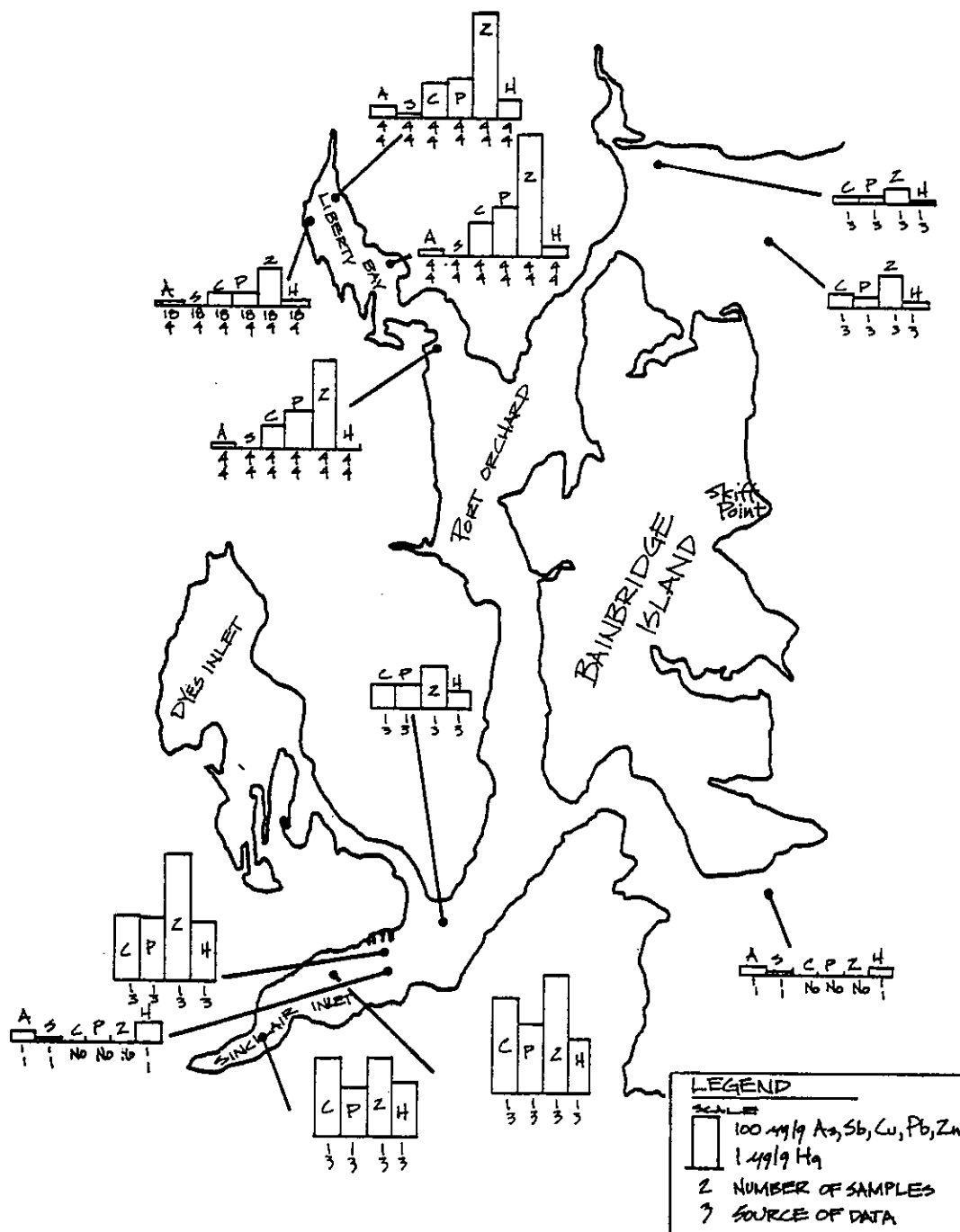
Figure VIII-3. Concentrations of Selected Trace Metals Observed in the Sediments of Sinclair Inlet and Other Areas of the Port Orchard System.

Data from 1) Crecelius et al., 1975; 3) Malins et al., 1980; 4) Cummins et al., 1976.

Levels in the Embayments

Budd Inlet. Available data for individual stations in Budd Inlet are presented in Figure VIII-2. While relatively few stations have been sampled, the present data indicate that sediments are at or near background levels. Highest concentrations of Cu, Pb, Zn, and Hg were observed at the extreme southerly station indicating a possible local influence. However, the sediments at this station were fine grained. Comparable levels were observed at the mid-inlet station and in sediments from other inlets in the Southern Sound which exhibited similar sediment characteristics. It appears likely, therefore, that Budd Inlet is presently not receiving significant anthropogenic inputs but is responding primarily to the deposition of fine-grained, organic-rich particles.

Sinclair Inlet. Individual station data for Sinclair Inlet and surrounding regions are presented in Figure VIII-3. As with Budd Inlet, the data are limited, but in this case they indicate an impact of local anthropogenic input in the western section. This area contains predominantly fine-grained, organic-rich sediments, but the concentrations of Cu, Pb, Zn and Hg are all much higher than observed in sediments of comparable characteristics from non-urbanized areas. Concentrations of As and Sb (measured at one station) do not show marked elevation above background.

The limited flushing of the inlet undoubtedly contributes to the retention of local inputs. While greater single-station concentrations of all metals have been observed in Elliott and/or Commencement Bays, the uniformity of the high levels throughout Sinclair Inlet indicates more pervasive contamination over a larger spatial extent than in most other areas. It should be noted in particular that the concentrations of Hg were among the highest observed in the Sound (Figure VIII-1).

Commencement Bay. The available data from Commencement Bay (Figure VIII-4) present a complex pattern of metal deposition. Outside of the waterways, the northern and mid sections of the bay had concentrations of all of the metals very near or below the values expected from comparison with non-urbanized areas. Conversely, excess concentrations of all metals were observed all along the southern shore. These data in general are consistent with the locations of known and probable sources of trace metals along the southwest shore. The latter include combined sewer overflows and storm drains, a sewage treatment plant discharge, and both liquid and solids (slag) discharges from the ASARCO Copper Smelter (Crecelius et al., 1975; WDOE, 1979).

The direct impact of the latter discharges is readily apparent from the extremely high concentrations of As and Sb observed in the sediments (slag) in the western bay. From the constituency of the liquid effluent (see sources section, below) it can be expected that these sediments also contain very high levels of Cu and Zn and may contain high levels of Pb. No direct measurements of these metals in the slag sediments have been made. However, concentrations in the sediments from just south of the slag deposit were observed to be elevated compared to background sediments (Figure VIII-4).

While the ASARCO discharges constitute one of the largest single inputs of trace metals, the dominant northwesterly flow along the southwestern shore apparently minimizes much of the impact within Commencement Bay. Significantly higher levels of As and Sb have been observed, however, in sedimentation areas at Quartermaster Harbor (As levels of 50 μg/g) and south of Fox Island (As levels of 39 μg/g) in the Southern Sound. Most of the samples of deep sediments from East Passage (As averaged approximately 30 μg/g) also have shown elevated As and Sb concentrations compared to other Main Basin sediments. Much of this widespread contamination has been attributed to atmospheric emissions from the ASARCO plant (Crecelius et al., 1975).

High levels of Cu, Pb, Zn, and Hg were observed in the Hylebos and City Waterways, both highly industrialized and poorly flushed. The highest observed concentrations of Cu, Pb, and Zn in Commencement Bay were found in one sample from the Sitcum Waterway. The levels of metals reported for this sample are so much greater than normally observed that it appears likely that the sample consisted either of spilled metal ore or possibly smelter slag. Consistent with this possibility is the fact that other metals were also observed at high concentration in this sample, including Ag (10.8 μg/g), Cd (16.2 μg/g), Mo (114 μg/g), Sn (65 μg/g), W (51 μg/g) and probably As and Sb (Malins et al., 1980). However, the accuracy of these latter measurements has not been confirmed independently.

Similar to the distribution of ASARCO wastes, the contamination of these waterways does not appear to be detectable within the bay itself, but rather seems to represent local accumulations from shore-based activities within the poorly flushed waterways.

Only limited data have been collected on the trace metals levels in the lower Puyallup River (D. Tangarone, U.S. EPA, Region X, unpublished data, 1980). However, these data and the general lack of significant contamination of most of Commencement Bay, and particularly the near background levels observed at a dump site located just off the river mouth, argue that the Puyallup is at natural levels.

Figure VIII-4. Concentrations of Selected Trace Metals Observed in the Sediments of Commencement Bay.

Data from 1) Crecelius et al., 1975; 2) Malins et al., 1980; 8) D. Tangarone, U.S. EPA, Region X, unpublished data, 1980.

Duwamish River. The highest concentrations of Pb, Zn, and Hg and the second highest Cu values in the Sound, have been observed in the lower reaches of the Duwamish River estuary (Figure VIII-5). This section of the river is clearly impacted by a number of sources including combined sewer overflows and storm drains, and by shore-based activities, particularly the shipyards on Harbor Island. At the same time, the salt-wedge in the deeper waters tends to reduce the river flushing and generates a net upstream transport in the deep layers. These factors favor the retainment of even fine particulates within the estuary.

Values of all of the metals are at or near background concentrations in the upper reaches of the navigable channel (Figure VIII-5), but the concentrations of Cu, Pb, and Zn increase markedly just south of Slip 1 and remain at high levels downstream of this point. From the available data, each of the three metals exhibits a slightly different spatial trend. Cu concentrations increased by about a factor of two at Slip 1 compared to the upstream reaches, and tended to increase fairly regularly downstream with maximum values noted at the mouth of the West Waterway. Lead concentrations show similar behavior except that the maximum Pb concentration (approximately 1.3 percent Pb) was observed below the Lander Street storm drain from Harbor Island into the West Waterway with decreasing levels to the north (METRO, 1980).

Maximum Zn concentrations (6700 ppm) were noted just south of Slip 1. The data indicate that downstream from this site the Zn levels tend to be high but variable and much less than the extreme value. However, the study (METRO, 1980) which yielded the highest Cu and Pb values, sampling along the eastern shore of the West Waterway, did not include Zn in the analyses. As a result, higher Zn levels may exist in the waterway than were observed in the studies summarized in Figure VIII-5.

These trends in the distribution of metals in the sediments are consistent with localized impacts from three identifiable sources:

1. Inputs of Cu, Pb, and Zn via the Diagonal Way combined sewer overflow, just south of Harbor Island, and smaller combined sewer overflows and storm drains in the lower river. Similar high enrichment of metals were apparent near the Hanford Street combined sewer overflow in the East Waterway and near the Denny Way combined sewer overflow in Elliott Bay north of Pier 71 (Figure VIII-6).

2. A strong source of Pb in the storm drains of western Harbor Island which carry dust contaminated by the activities of a secondary lead smelter on Harbor Island. Dust samples containing 18 percent Pb have been noted in the vicinity of the smelter (PSAPCA, 1980).

-291-
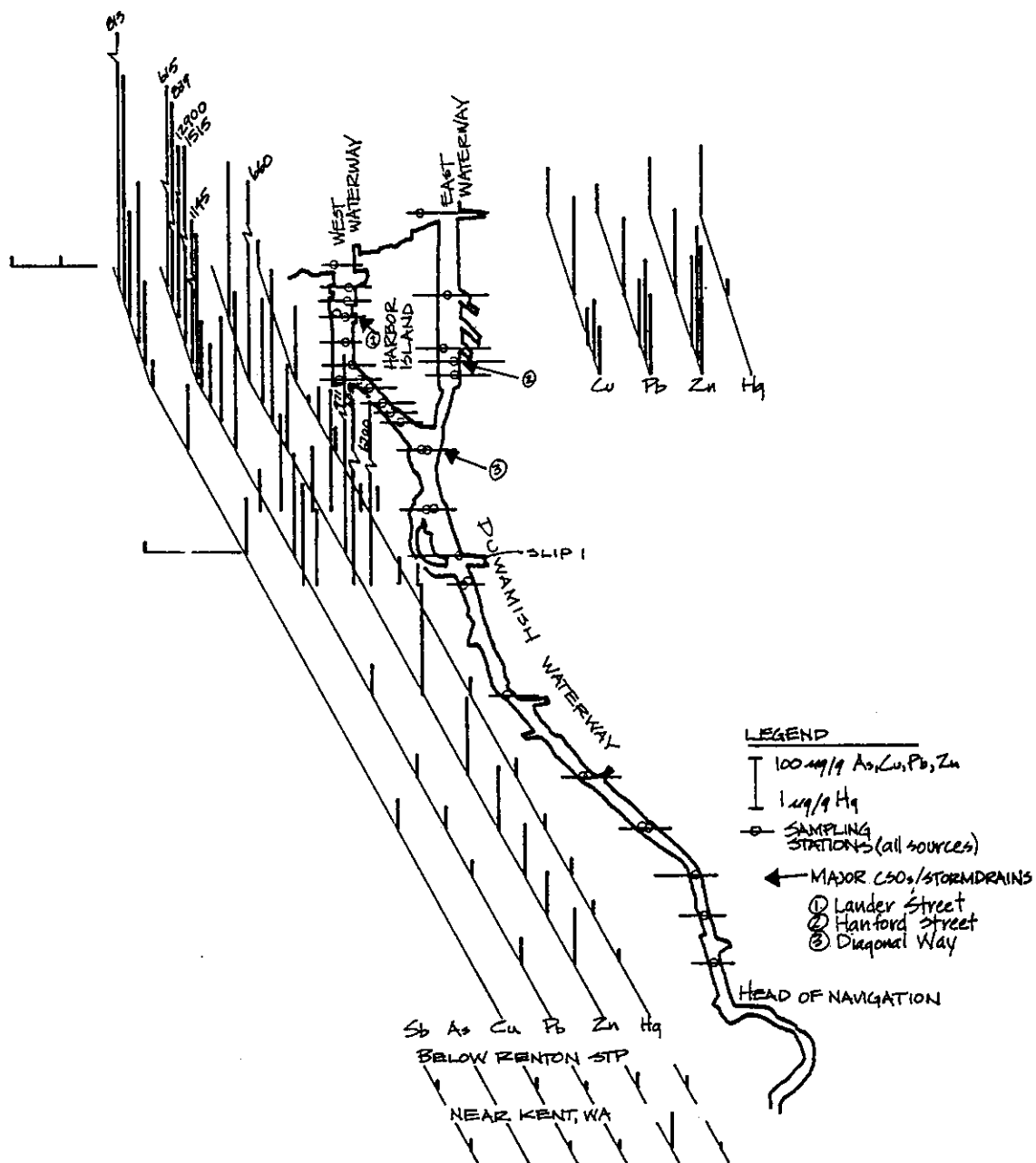
Figure VIII-5. Concentrations of Selected Trace Metals Observed in the Sediments of the Duwamish River.

Data from J.N. Blazevich, U.S. EPA, Region X, unpublished data, 1973; METRO, 1980; Malins et al., 1980; Tomlinson et al., 1976; Blazevich et al., 1977; D. Tangarone, U.S. EPA, Region X, unpublished data, 1980.
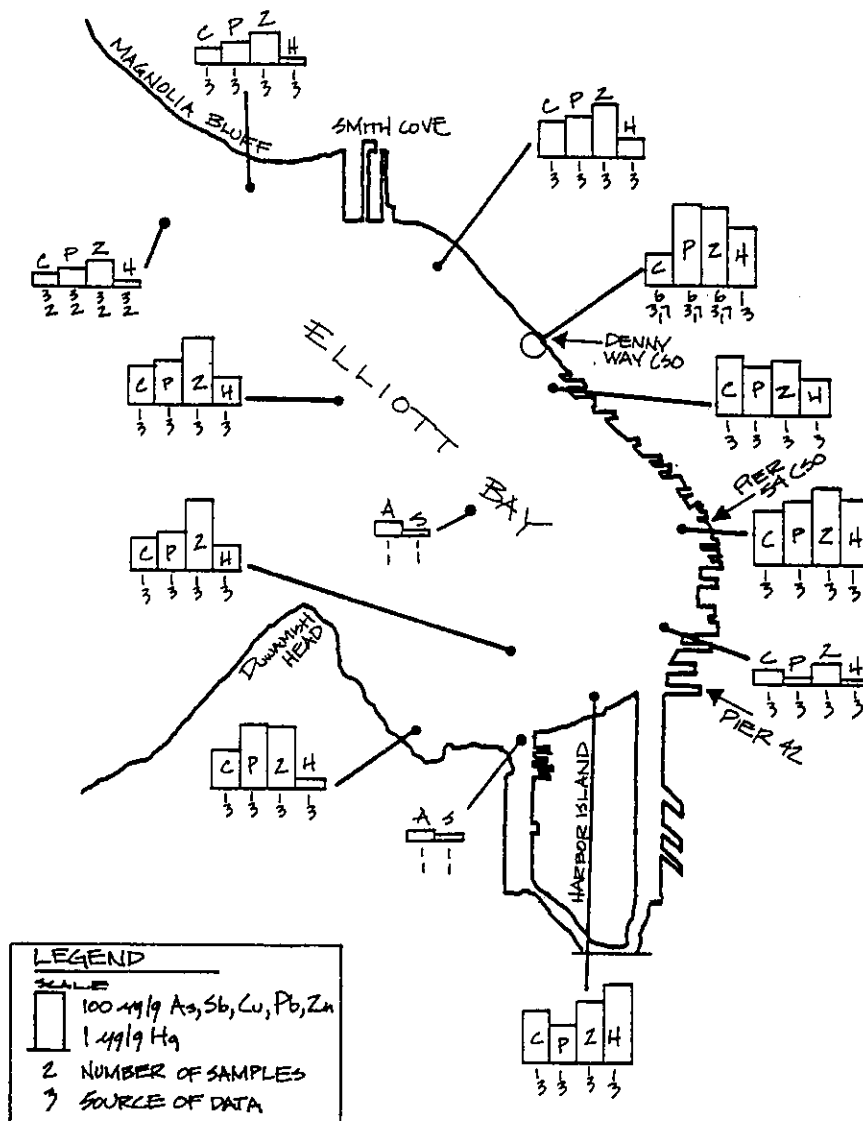
Figure VIII-6. Concentrations of Selected Trace Metals Observed in the Sediments of Elliott Bay.

Data from 1) Crecelius et al., 1975; 2) Schell et al., 1976; 3) Malins et al., 1980; 7) Tomlinson et al., 1976.

3. A major input of Cu from the Harbor Island shipyards and dry docks.

Besides the high levels of trace metals observed in the river, it is important to note the very high concentration gradients implicit in these data. For example, Pb concentrations varied more than an order of magnitude in a few hundred meters in the West Waterway. These distributions imply one or more of the following: limited movement and transport of the contaminants from the source; rapid dilution of the mobile material to near background levels within a short distance; and patchy accumulation in the sediments. While relatively intense sources of trace metals are obviously present, their impact on the trace metals budget of Puget Sound in general appears to be small.

Elliott Bay. Receiving the discharge of the Duwamish River, inputs from combined sewer overflows and storm drains and probably other direct sources, it is not surprising that the concentrations of Cu, Pb, Zn, and Hg were observed to be higher in Elliott Bay than in the reference areas and most of Commencement Bay and Budd Inlet. No clear spatial trends within the bay are evident in the available data (Figure VIII-6), in part because the samples are limited in number and many were biased toward known input sources. In addition, it appears that in-bay levels of Cu, Pb, and Zn were strongly dependent on the grain size of the sediments (see discussion below), a dependence which argues for fairly uniform levels of contamination with the sedimentation process being the dominant controlling factor. Comparatively, the Hg levels appeared to be more strongly dependent on the intensity of local sources. High levels of Hg were observed near both the Denny Way and Pier 54 combined sewer overflow discharge sites, and just off the north end of Harbor Island. Levels of Hg tended to decrease from the Seattle waterfront to the north and west.

What appears to be abnormally low levels of all metals near Pier 42 in the southeast bay probably was related to recent dredge and fill operations at this site for the construction of new piers. The sediment texture was comparatively coarse and the metals were at or near background levels.

In general, the levels of Cu and Zn in the bay were approximately 2 to 3 times that observed in background sediments of comparable grain sizes (Cu averaged approximately 60 $\mu g/g$, Zn about 115 $\mu g/g$). Greater overall enrichment was observed for Pb (average 100 $\mu g/g$) and Hg (average 0.56 $\mu g/g$), roughly 6 and 7 times the reference areas, respectively. The high Pb levels are consistent with the presence of strong sources on Harbor Island of both direct inputs from street runoff and possible wind transport of dust, and numerous combined sewer overflow and storm drain inputs. Discrete sources for Hg, other than combined sewer overflows and storm drains, have not been identified.

DISTRIBUTION IN THE WATER COLUMN

The concentrations and distribution of trace metals in the water column in Puget Sound have received only limited study. This small data base is insufficient to establish precise estimates of the spatial and temporal trends in a rapidly changing system like the Sound, but does provide an indication of the dominant processes involved.

The total concentrations of trace metals in the water column consists of the sum of the dissolved and particulate phases. While the levels in these phases are related through geochemical processes, it is appropriate to initiate the review of the available data by considering each phase independently.

Dissolved Metals

The concentrations of dissolved (that fraction passing a filter of from 0.5 μ to 0.22 μ pore size) have been measured in the Sound for As, Cu, Pb, and Zn (Table VIII-2). Arsenic was measured in 14 samples from the northern Main Basin and found to average about 1.5 $\mu g/l$ ±10 percent standard deviation (Crecelius et al., 1975). No significant vertical trends were apparent. Dissolved Cu concentrations were generally in the range between 0.2 and 0.4 $\mu g/l$ in samples from the Main Basin, Elliott Bay and Commencement Bay while Zn averaged 2 $\mu g/l$ to 3 $\mu g/l$ (Schell et al., 1976 and 1977; Tatomer, 1973). These values agree with those observed in waters from the Strait of Georgia (Thomas and Grill, 1977) and from Saanich Inlet and Lake Nitnat (Sugai, 1975; Lieberman, 1979).

Dissolved Pb concentrations in excess of 7 $\mu g/l$ have been reported, with an average level of about 3 $\mu g/l$ (Schell et al., 1976). However, the values for Pb are suspect and unsupported by other studies (Schell and Nevisi, 1977). They are much higher than is generally expected for ocean waters, particularly since other studies indicate that most Pb in sea water should be bound to particulate phases (Benninger et al., 1975; Zirino and Lieberman, 1975). No additional, reliable sources of dissolved Pb data were identified.

No direct measurements of dissolved Hg in the Sound have been reported. Bothner observed values of about 0.015 $\mu g/l$ in Bellingham Bay (Bothner, 1973) and it does not seem unreasonable to expect similar values in most of the Sound.

At the present time only limited information on the spatial trends in the concentrations of dissolved metals is available. Tatomer (1973)

observed elevated Cu concentrations (up to 4 µg/l) in Commencement Bay near the ASARCO Smelter. This was attributed to effluent from the latter facility (see also sources section, below). The data for the remaining metals have not documented significant spatial variability, either among subregions or vertically in the water column with the exception of one series of samples collected from Skiff Point (Bain-bridge Island; Schell et al., 1977). The concentrations of dissolved Zn in the upper 20 m at this station were roughly twice as high (4 to 5 µg/l) as observed in the deep water at that station (1 to 2 µg/l). Copper concentrations were uniform with depth. These samples were collected in December when riverine inputs to the surface layer would be large.

Particulate Metals

The concentrations of trace metals associated with the suspended particulate matter in the Sound have also received limited study. Expressed in a whole volume basis, As, Cu, PB, and Zu associated with the particulates all generally have been observed at levels of 0.5 µg/l or less in the Main Basin (Crecelius et al., 1975; Schell et al., 1976). However the concentrations were dependent on the amounts of particulate matter in the water column and hence have been observed at much higher levels in more turbid areas, e.g., near rivers' mouths (Riley et al., 1980).

Due to the strong dependence of the levels of trace metals on the particulate load when the concentrations are expressed as a whole volume basis, a more convenient approach is to express the concentrations as a function of the mass of particulate matter, e.g., µg metal per g dry particulates. Available data for the concentrations of the metals in regions of Puget Sound, on a dry particulate mass basis, are included in Table VIII-2.

These data indicate that the concentrations associated with the particulates for all of the trace metals are significantly higher than observed in most of the sediments. In addition, the concentrations of Cu, Pb, and Zn appear to be enriched in the Main Basin near the West Point Outfall, in Elliott and Commencement Bays and Sinclair Inlet compared to the rest of the Sound. Both of these observations result in part from the fact that many of these samples were collected near sources of contamination and hence may be biased toward high values (Riley et al., 1980). In part, however, the results reflect the effect of varying the constituency of the particulate matter. As discussed in more detail below, the comparatively high levels appear to result from the small particle size of the suspended matter while much of the regional variability was due to differences in the fraction of lithogenous inorganic material constituting the particles.

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TABLE VIII-2

CONCENTRATIONS OF SELECTED TRACE METALS IN THE WATER AND SUSPENDED PARTICULATE MATTER FROM PUGET SOUND

| Region | Concentrations of Metals | | | |
	As	Cu	Pb	Zn
Dissolved (µg/l) Main Basin	$1.5 \pm 0.15(14)^{a,b}$	$0.39 \pm 0.18(56)^{c}$	ND[d]	$1.98 \pm 1.23(55)^{c}$
Particulates (µg/g)				
Main Basin	ND	$<166 (39)^{b,c}$	ND	$471 \pm 363 (39)$
Main Basin[e,c]	ND	$171 \pm 99 (4)$	$220 \pm 39 (4)$	$399 \pm 92 (4)$
Elliott Bay[f] (South end)	$34 \pm 11 (3)$	$206 \pm 26 (3)$	$389 \pm 56 (3)$	$673 \pm 197 (3)$
Commencement Bay[f] (Waterways)	73 (2)	191 (2)	181 (2)	360 (2)
Sinclair Inlet[f]	31 (1)	130 (1)	146 (1)	490 (1)
Budd Inlet[f]	<22 (1)	47 (1)	26 (1)	180 (1)
Port Madison[f]	28 (1)	68 (1)	97 (1)	280 (1)

a Mean and one standard deviation. Number in parentheses refers to number of samples constituting the mean.

b Crecelius et al., 1975.

c Schell et al., 1976 and 1977. Collected near West Point Outfall.

d ND indicates no data available.

e Data from sediment traps near the West Point Outfall.

f All data from Riley et al., 1980.

In comparison with the concentrations of dissolved metals, the contribution of particulate As and Zn to the total levels in the water column appear relatively minor at average suspended particulate concentrations. On the other hand, for Cu, and probably for Pb, the data indicate that much of the metals in the water column may be associated with the particulates.

SOURCES OF TRACE METALS

There are numerous inputs of trace metals to the Sound, including both natural and anthropogenic sources. As pointed out earlier, the general indication obtained from the data on the distribution and concentrations in the Sound is that natural sources predominate except for limited areas in close proximity to strong inputs and, to a lesser extent, in areas of poor flushing. At the same time, as with most facets of the Sound, studies of trace metals' inputs are limited. Those areas for which reasonable estimates can be made are presented in the following discussion.

Riverine Transport

Recent measurements of the total concentrations of trace metals (dissolved plus particulate) transported by rivers discharging into Puget Sound are presented in Table VIII-3. (Note that the particulate concentrations of the metals were measured on a whole volume basis and hence are not directly comparable to the data in Table VIII-2). These metals are generally considered to represent the natural loading associated with dissolution and erosion within the watersheds. The data are very limited, particularly regarding the seasonal changes in the discharge rates of the metals and in the separate determination of the concentrations of dissolved and particulate metals. Since the few data available indicate that the metals predominantly are associated with the particulates, the metals' transport to the Sound should peak during high flow periods, coincident with the peak sediment discharge. Quarterly data collected on the Skagit River (USGS, 1978 and 1979) generally support this view.

To reasonably estimate the inputs, the dissolved and particulate inputs were treated as separate loads. The data for the dissolved phase were reasonably uniform with little seasonal variations. The dissolved concentrations of As were generally 1 μg/l or less, while Cu and Pb concentrations were generally in the range of 1 to 3 μg/l, and Zn approximately 5 μg/l (USGS, 1978 and 1979; Crecelius et al., 1975).

While reasonable estimates of the total suspended sediment load have been developed (see Sedimentation Chapter), the concentrations of trace metals associated with those sediments has been very poorly

TABLE VIII-3

CONCENTRATIONS OF SELECTED TRACE METALS IN RIVERS AND LAKES
TRIBUTARY TO PUGET SOUND ON WHOLE VOLUME BASIS

Concentrations of Trace Metals, $\mu g/l$

	As[f]			Cu			Pb			Zn			Hg		
	D[f]	P[f]	T[f]	D	P	T	D	P	T	D	P	T	D	P	T
Skagit[a] n=8[h]	0.8	1.4	2.1	2.4	9.9	10.4	1.9	11.3	14.7	6.3	11.3	17.5	0	0.25	0.25
Duwamish[b,c] n=4	-[g]	-	<2	-	-	4.7	-	-	3.3	-	-	15.0	-	-	0.25
Puyallup[c] n=1	-	-	<2	-	-	4	-	-	6	-	-	15	-	-	0.44
Nisqually[a] n=12	1.3	-	-	1.7	-	-	5.1	-	-	2.8	-	-	0.02	-	-
Lake Washington[d] n=15	-	-	-	-	-	3.6	-	-	2.1	-	-	25	-	-	-
Cedar River[d] n=1	-	-	-	-	-	1.7	-	-	0.6	-	-	17	-	-	-
AVERAGE	1	-	2[e]	2	-	5	3	-	5	5	-	18	0	-	0.3

[a]USGS, 1978 and 1979. [b]Blazevich et al., 1977. [c]D. Tangarone, U.S. EPA, Region X, unpublished data.

[d]Barnes, 1976. [e]Including estimates of 0.9 $\mu g/l$ from Crecelius et al., 1975.

[f]D, P and T refer to dissolved, particulate and total metals, respectively.

[g]A dash indicates no or insufficient data were available.

[h]n refers to the number samples constituting the averages.

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established. Crecelius et al. (1975), reported the results of samplings for particulate As and Sb in Puget Sound rivers in June, September, and December. The concentrations were generally uniform among the sampling periods, i.e., no major seasonal effect was noted. Concentrations for both As and Sb were roughly six times higher in the more northerly rivers; i.e., As was about 30 μg/g in the Skagit, Stillaguamish, Snohomish, and Duwamish Rivers, versus approximately 6 μg/g for the Puyallup, Nisqually, Dosewallips, and Duckabush. These differences seem to reflect the mineralogy of the drainage basins. More major mineral deposits have been identified in the northern Cascades (from King County north) than in the southern mountains (PNRBC, 1970, Appendix IV).

Comparable investigations for metals other than As and Sb have not been performed. The concentrations of Cu, Pb, and Zn observed on particulates in local freshwater systems are summarized in Table VIII-4. Of these values, the data from the Skagit River (USGS, 1978 and 1979) probably are biased toward high values due to low analytical precision at low concentrations of metals. The one sample collected when the suspended load was high yielded Cu and Zn concentrations of 43 μg/g and 64 μg/g, respectively. No reliable Pb data were obtained under the same conditions. For comparison, the As value reported from this source (USGS, 1979) was 13 μg/g, reasonably close to the levels of 20 ± 6 μg/g reported by Crecelius et al. (1975).

The concentrations of trace metals observed in Lake Washington (Table VIII-4), obtained from material collected in a deep sediment trap, are possibly biased for two reasons, first, because the trap material should represent finer suspended sediments, which have entered the lake circulation, than that normally encountered in the rivers. In addition, it was observed that the effluent from a storm drain may constitute part of the sample (Tomlinson et al., 1978).

Similarly, the levels observed in the Puyallup River (Table VIII-4) were based on samples collected at a station in the estuary (salinity was 8.3⁰/oo). Therefore much of the coarser material may have settled prior to this point. Also, salinity-induced exchange reactions between the particulate and dissolved phases may have altered (either increased or decreased) the concentrations of the metals (see discussion below).

It must be concluded, therefore, that the available values of the concentrations of Cu, Pb and Zn associated with the riverine particulates are of questionable accuracy. However, to obtain an estimate of the loading to the Sound from this source, concentrations of particulate Cu and Zn of 100 μg/g and 200 μg/g, respectively, are considered to be reasonably representative of the data. On the basis of the correspondence of Cu and Pb concentrations in bedded sediments (see Figure VIII-7, Sediment and Particulate Relationships, below), an estimate of 100 μg/g

TABLE VIII-4

CONCENTRATIONS OF TRACE METALS ON PARTICULATES IN
PUGET SOUND REGIONAL FRESHWATER SYSTEMS ON DRY MASS BASIS

Region	Concentrations of Metals (μg/g)			
	As	Cu	Pb	Zn
Skagit River				
All Samples	$28 \pm 16(14)^{a,b,c}$	$213 \pm 189(5)^{d}$	$293 \pm 269(3)^{d}$	$347 \pm 419(8)^{d}$
At high suspended load	$13(1)^{d}$	$43(1)^{d}$	$<215^{d}$	$64(1)^{d}$
Duwamish River	$26 \pm 11(6)^{b}$	ND	ND	ND
Puyallup River	$6.9 \pm 2.6(10)^{b,e}$	$156(1)^{f}$	$153(1)^{f}$	$360(1)^{f}$
Lake Washington	ND	$61 \pm 39(7)^{g}$	$183 \pm 54(7)^{g}$	$241 \pm 102(7)^{g}$
Fraser River	ND	ND	ND	$171 \pm 18(4)^{h}$

a Mean and one standard deviation. Number in parentheses refers to number of samples constituting the mean. ND indicated no data available.

b Crecelius et al., 1975.

c This average includes data from the Stilliguamish and Snohomish Rivers.

d USGS, 1978 and 1979.

e This average includes data from the Nisqually, Dosewallips, and Duckabush Rivers.

f Riley et al., 1980.

g Tomlinson et al., 1978.

h Grieve and Fletcher, 1977.
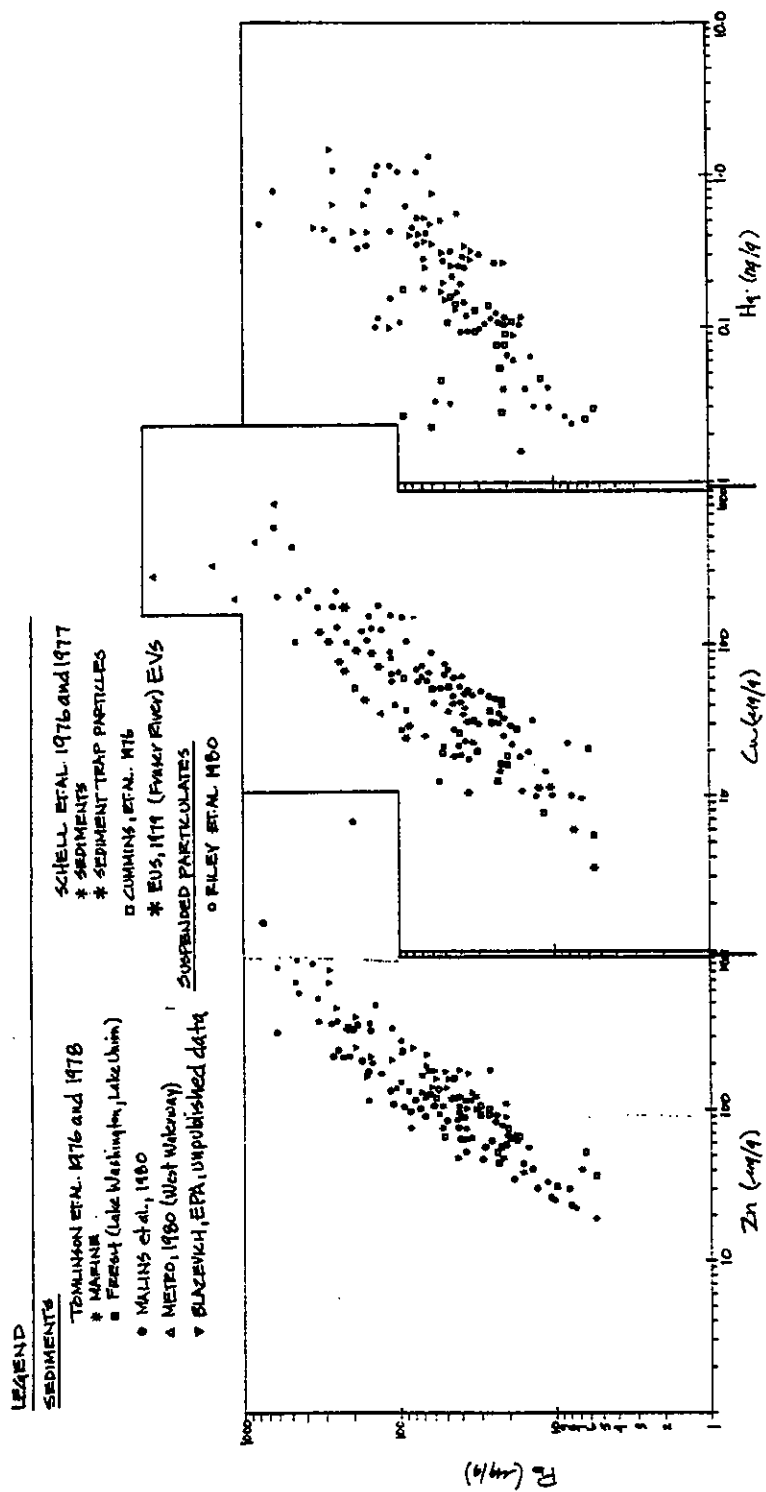
Figure VIII-7. Scatter Plots of the Observed Concentrations in the Sediments from Puget Sound, Lake Washington, and the Fraser River of Pb versus the Concentrations of Cu, Zn, and Hg.

for Pb also appears reasonable. All of these values could easily be in error by at least ± 50 percent.

Based on these estimates of the concentrations of the dissolved and particulate-associated metals, and the average annual water and sediment discharges from all of the rivers in the indicated subregions, the inputs of trace metals associated with the riverine transport were calculated and are presented in Table VIII-5.

TABLE VIII-5

ESTIMATED ANNUAL INPUTS OF
TRACE METALS FROM RIVERINE DISCHARGES

	Average Annual Discharge									
	Water[a]	Sediment[b]	Metals, Metric Tons/Year							
	Discharge	Discharge	As		Cu		Pb		Zn	
Area	$\times 10^{12}$ l/yr.	$\times 10^{11}$ g/yr.	Diss.	Part.	Diss.	Part.	Diss.	Part.	Diss.	Part.
Whidbey Basin	26	21	26	53	52	190	52	190	130	380
Main Basin	5.3	6.3	5.3	7.6	10.6	63	10.6	63	27	126
Southern Sound	2.1	1.7	2.1	1.2	4.2	17	4.2	17	10.5	34
Total	33.0	27.0	33.4	61.8	66.8	170	66.8	270	167.5	540
TOTAL			95		337		337		708	

a Water discharge data summarized in Table II-2.
b Sediment discharge data summarized in Table IV-1.

It must be kept in mind, however, that in comparing these data with those from other input sources, the values for the average annual inputs tell only part of the story. In the first place, the riverine discharges are neither spatially nor temporally uniform. For example, the data in Table VIII-5 indicate that roughly 70 percent of the total river-borne metals entering Puget Sound are discharged into Whidbey Basin. Secondly, rapid sedimentation of the suspended load (see Sedimentation Chapter) may limit the zone of major influence to within a short distance of the rivers' mouths. Finally, it must be noted that much of the river discharge, and particularly the suspended sediment discharge, occurs during the high flow conditions of early winter (See Figure II-7 and Table IV-4). As a result of these factors, the concentrations of trace metals associated with river discharges would be expected to be greatest during winter and minimal during late summer/early fall.

Shoreline Erosion

As noted earlier (Sedimentation chapter), erosion of shoreline materials may constitute a contribution to the sediment mass loading of the Sound as large as or greater than the riverine inputs. This eroding material can be expected to have natural trace metal content similar to other regional soils. These concentrations for a number of elements were presented in the third column in Table VIII-1, based on the analysis of single samples of glacial deposits from nine locations in northern Puget Sound, including five shoreline sites in Whidbey Basin (D. Pevear, Western Washington State University, personal communication). How representative these value are of all eroding soils is not known; however, little variation for most metals was noted among the sites.

Based on these concentrations and average annual sediment mass inputs of about 3×10^{12} g/yr, estimated previously (Sedimentation Chapter), the inputs of As, Cu, Pb, and Zn were calculated. These values are included in the summary table (Table VIII-8 below). Considering the uncertainties of both the sediment mass input values and of the concentrations of metals associated with the eroding soils, these values must be considered rough estimates.

Advection

The largest single volume input of water to the Sound is that of the seawater from the Strait of Juan de Fuca which is transported through Admiralty Inlet. This flow of seawater is approximately 10 times the average river discharge, and may be a major source of natural trace metals to the Sound. Little data could be found which provides an estimate of the concentrations of trace metals in the incoming seawater.

A number of studies have used values obtained from the deep water from the northern Main Basin (Crecelius et al., 1975; Schell et al., 1977). However, since this water may consist of about two-thirds surface water refluxed back after mixing in Admiralty Inlet, it may not be representative of the incoming seawater. Thomas and Grill (1977) report values of 0.5 μg/l and 5 μg/l for dissolved Cu and Zn, respectively, in deep waters of the eastern Strait of Georgia. The concentrations of Cu appear to be equivalent to the levels reported for the deep waters of Puget Sound, while the concentrations of Zn appear to be roughly twice those observed in the Sound.

Holton et al. (1978) measured the concentrations of dissolved and particulate Cu, Pb, and Zn in 8 samples of high salinity water off the mouth of the Columbia River. The observed values were:

Concentrations of Metals, μg/l

Cu		Pb		Zn	
Diss.	Part.	Diss.	Part.	Diss.	Part.
0.37±0.16	0.2	0.017±.005	0.022	1.29±1.64	0.30

These values for Cu and Zn agree with levels of about 0.5 μg/l and 3 μg/l, respectively, observed in the Main Basin (Schell et al, 1976); the Pb values are considerably lower.

The limited data may introduce considerable error into any calculation of the advective inputs of the trace metals. In addition, it should be noted that since no strong vertical gradients in the concentrations of trace metals have been observed in the Main Basin or Admiralty Inlet, the input is probably nearly balanced by the output so that there is essentially no net advective transport.

At the same time, obtaining at least order-of-magnitude estimates of the advective inputs is useful in providing a comparison of the natural advective fluxes with those of other sources. For lack of better data, this input calculation was performed using the average concentrations of the metals observed in the Main Basin (Table VIII-2), assuming the concentration of suspended particulate matter was 2 mg/l, and that the advective inflow of water is 4×10^{14} l/yr (Chapter 2). For example, dissolved Cu averaged 0.39 μg/l, while the average concentration was 135.5 μg/g on the particulates. At 2 mg/l, the latter yields 0.27 μg Cu/l associated with the particulates for a total of 0.66 μg Cu/l. The calculated inflow is thus 264 mt/year (0.66 μg/l x 4×10^{14} l/yr). Similar calculations yielded values of 630 mt/yr, 140 mt/yr, and 1120 mt/yr for As, Pb and Zn, respectively.

Municipal and Industrial Effluent

Available data for the concentrations and input rates for As, Cu, Pb, and Zn from industrial and municipal waste discharges are presented in Tables VIII-6 and VIII-7, respectively. Most of these data represent the result of one or a few samplings of the effluent. Both municipal and industrial discharge characteristics can vary considerably over time and among sources as a result of differences in the inputs to the municipal systems and process variations in industrial plants. Therefore, the effluent concentrations must be considered only approximately representative of the average discharge levels. For purposes of estimating the loading to the Sound, it was assumed that the arithmetic averages of the observed municipal effluent concentrations for each metal (Table VIII-6) were representative of all municipal discharges. Similarly, the averages of the levels reported for the two pulp and paper company effluents (Table VIII-7) were assumed to be representative of all similar discharges. It must be recognized that there may be errors of unknown magnitude associated with these assumptions.

While other industries are known to discharge directly to the Sound, these discharges are relatively small in volume and thus, even at very high concentrations of trace metals, would not make a major contribution to the levels of metals in the system (U.S. EPA, Region X, unpublished data, 1980).

Atmospheric Inputs

Recent measurements of combined dust and rain fallout in the Seattle area and the Lake Washington watershed indicate that atmospheric inputs of metals may be significant (Spyridakis and Barnes, 1978). Similarly, Crecelius et al. (1975) have indicated that As emissions from the ASARCO smelter can be detected in fallout and in the sediments of Lake Washington, Quartermaster Harbor and East Passage. Based on the former measurements, which show decreasing values downwind from the Seattle metropolitan area, and using the annual average atmospheric particulate distributions over the Sound to estimate areas of similar fallout rate (PSAPCA, 1979), the whole Sound average annual inputs of As, Cu, Pb, and Zn were calculated. These values are summarized in Table VIII-8, below.

However, these input rates are based on relatively few measurements which were made in Seattle and eastward. Since the direction of the wind flows over the Sound generally have a westerly component, much of the eastern-shore emissions would be expected to move overland, not over the Sound. In addition, Murray and Gill (1978) discounted atmospheric transport as a major source of iron (Fe) to the Sound since no surface excesses of Fe were observed which were not explainable as the effect of riverine inputs. The values calculated for atmospheric inputs thus probably represent upper limit and may significantly overestimate the importance of this source.

TABLE VIII-6

CONCENTRATIONS AND ANNUAL INPUT RATES OF TRACE METALS FROM MUNICIPAL SEWAGE EFFLUENTS

Source	Concentrations of Metals, μg/l			
	As	Cu	Pb	Zn
Municipal Effluents				
West Point STP[a]	ND[g]	172	82	362
Tacoma STP[b]	14	42	1.5	141
Everett STP[c]	ND	16	ND	50
AVERAGE	14	77	42	184
CSO's + Storm Drains[d]				
Denny Way CSO (Elliott Bay)	ND	77	385	285
Madison Park CSO (Lake Washington)	ND	52	57	125
Storm Drains (Lake Washington, Elliott Bay)	ND	42	218	99
Hanford Street CSO (Duwamish River)	ND	110	480	340
AVERAGE	ND	70	285	212

ESTIMATED TOTAL ANNUAL DISCHARGES

Effluent, l/yr.	Metals, Metric Tons/Year			
Municipal				
2.5×10^{11}[e]	3.5	19	11	46
CSO's and Storm Drains				
6.0×10^{9}[f]	ND	0.42	1.7	1.3
TOTAL MUNICIPAL, METRIC TONS/YR	3.5	19.4	12.7	47.3

a. Healy, 1979.
b. City of Tacoma, 1979.
c. Zafiropoulos, 1976.
d. Tomlinson et al., 1976 and 1978.
e. Birke et al., 1980.
f. Tomlinson et al., 1976.
g. ND indicates no data.

TABLE VIII-7

CONCENTRATIONS AND ESTIMATED
ANNUAL INPUT RATES OF TRACE METALS
FROM INDUSTRIAL WASTE EFFLUENTS

PULP AND PAPER MILLS[a]

	Concentrations of Metals, µg/l			
	As	Cu	Pb	Zn
	5	80	8	97

ESTIMATED TOTAL ANNUAL DISCHARGES

Effluent, 1/yr.	Metals, Metric Tons/Year			
2.5×10^{11} [b]	1.3	20	2	24

ASARCO[c]

	Concentrations of Metals, µg/l			
Outfalls	As	Cu	Pb	Zn
North	8	40	BD[d]	20
Middle	2700	2100	BD	1400
South	3900	1600	20	2200

ESTIMATED TOTAL ANNUAL DISCHARGES

Effluent, 1/yr.	Metals, Metric Tons/Year			
(N) 0.9×10^9	.01	0.04	0	0.02
(M) 1.9×10^9	4.8	3.8	0	2.5
(S) 2.0×10^9	8.1	3.3	0.04	4.6
TOTAL INDUSTRIAL INPUTS, METRIC TONS/YR	14	27	2	31

a. D. Tangarone, U.S. EPA, Region X, unpublished data, 1980.
b. Birke et al., 1980
c. WDOE, 1979
d. BD = Below detection.

Inputs from Ship Operations

Commercial and recreational vessel operations have been identified as a probable source of trace metals (Zafiropoulos, 1976). However, the quantitative contribution cannot be estimated reasonably due to the lack of sufficient data. Metals, primarily copper, are included in paint and polymer coatings on commercial and recreational boat hulls as biocides. Zinc is used as a sacrificial electrode to reduce corrosion of other metals on the vessels. In both cases, under normal operating conditions the metals' release is slow and probably does not constitute a major source. However, in marinas and harbor areas, localized impacts may be significant. The greatest loss of metals apparently occurs during drydocking when old coatings are removed. For example, this input appears to be a likely source of the high Cu concentrations observed in the sediments along the northwest side of Harbor Island (METRO, 1980).

In the stripping operation, one commonly used method has been to employ smelter slag as a sandblasting agent (D.W. Nay, Robert A. Barnes, Inc., personal communication). This material is hard, abrasive, and is favored for health reasons because it contains no free silica. The primary source of the slag in current use in Puget Sound is from a smelter site in British Columbia. The plant has been closed for many years and records of the metal(s) produced there are not available. Chemical analyses of the material are limited but indicate that it has significant quantities of Cu (approximately 1 mg/g). At an estimated annual use rate of the slag in the Puget Sound region in excess of 10,000 tons, the Cu input of greater than 10 mt/yr would be achieved if all of the spent slag were released in the Sound. However, usage and waste disposal practices have not been documented. In addition, considering the refractory nature of slag (Crecelius et al., 1975), it probably makes a small contribution to the overall levels of trace metals in Puget Sound.

Other Inputs

A number of other possible sources of trace metals can be listed, including treatment of marine pilings and other structures with antifouling coatings, corrosion of metal structures, and the indiscriminate disposal of metal scrap. No quantitative data are available for these sources. They are probably of minor overall contribution (Crecelius et al., 1975; Schell et al., 1976).

Summary of Inputs

The quantifiable input levels of trace metals are summarized in Table VIII-8. These estimates have been qualified in the separate discussions and should be used primarily to obtain rough comparisons of

TABLE VIII-8

SUMMARY OF ESTIMATED ANNUAL INPUTS OF
TRACE METALS TO PUGET SOUND

Source	Metals Input, Metric Tons/Year			
	As	Cu	Pb	Zn
Natural				
Riverine	.95	337	337	708
Shore Erosion	50	60	46	280
Advection	630	270	140	1120
Total	775	667	523	2108
Anthropogenic				
Effluents				
Municipal	4	19	13	47
Industrial	14	27	2	31
Atmospheric	77	20	60	50
Total	95	66	75	128
TOTAL INPUTS	870	733	598	2236

the relative magnitudes of the sources. It should be also noted that the input estimates derived in this report differ from others prepared previously, notably in mass balances calculated by Crecelius et al. (1975), Zafiropoulos (1976), Schell et al. (1977) and Carpenter et al. (1978). The differences derive from different assumptions and interpretations of the data used by the various authors, as well as from changes in the basic data used in the preparation of mass balances.

The major point which can be drawn from these data would seem to be that the identifiable anthropogenic inputs make a relatively minor contribution to the overall inputs. This agrees with the general levels of trace metals observed in the sediments and water column of the Sound. Of the anthropogenic sources quantified in Table VIII-8 essentially all discharge into open, well mixed waters, and only the discharge from the ASARCO Smelter appears to have produced a detectable impact in the regional sediments.

At the same time, it is clear from the distribution of trace metals in the sediments that localized areas have been contaminated. With the exception of the inputs from some CSOs, the shipyards and from the lead smelter on Harbor Island, the precise sources of these metals are largely unknown. In addition, chemical characterization of the metals in the sediments has not been performed so that neither the stability of the metals in the sediments nor their availability to resident biota can be estimated.

GEOCHEMICAL PROCESSES

The intent of this section is to provide an analysis of the available data to elucidate the geochemical processes acting to influence the levels and distribution of trace metals in Puget Sound. A large body of data exists, obtained in studies from other areas of the world, which examines many of these processes. But these data are rarely consistent among investigators and the dominant processes appear to be largely site specific, each responding to the particular characteristics of different regimes, e.g., differences in the minerology of particulate phases and in the amounts and/or types of organic matter. Thus it is not possible to determine a priori which of these processes are applicable to the Sound.

Correspondence of Trace Metal Concentrations

As an exercise primarily designed to test for systematic errors in the measured concentrations of the trace metals among various investigators, the concentrations of Cu, Zn, and Hg were plotted versus the concentrations of Pb in the sediments and particulates of Puget Sound and surrounding areas. These plots are presented in Figure VIII-7. Interestingly, the data not only indicate reasonable agreement among investigators, but also demonstrate a high degree of correlation among the concentrations of Pb and those of Cu, Zn, and to a lesser degree, Hg. The same relation-ships appear to be applicable at low levels, representative of non-polluted sediments, for most of the highly contaminated samples, and for both freshwater and marine sediments. This correlation might be expected in the unpolluted sediments where the levels may be determined primarily by the metals content of natural soils. However, at higher levels, the trends in the data could be achieved only by a strong correspondence of the concentrations in the source material and/or chemical control over the relative amounts which accumulate in the sediments. Since some deviations from the general relationship occur, particularly in the very contaminated samples, e.g., those from the lower Duwamish, it seems most likely that commonality of usage and hence in the source materials is characteristic of this region.

The relationship of Hg and Pb does not present as strong a correlation, indicating differences in the sources and/or chemistry of Hg compared to Cu, Pb, and Zn. Similar relationships with other trace metals could not be developed because of limited data.

Relationship of Particle Grain Size and Organic Matter Content

Generally, finer sediments accumulate higher concentrations of trace metals (e.g. see DeGroot et al., 1976). Explicit recognition of this dependence has received little attention in the Sound. Crecelius et al. (1975) observed strong correlations between fine sediment and the concentrations of As, Sb, and Co in non-polluted sediments from Puget Sound. Mercury and Fe showed poorer correlations.

Similarly, data from a recent study of the levels of trace metals in the sediments of Elliott and Commencement Bays and Budd and Sinclair Inlets (Malins et al., 1980), also tend to correlate with grain size, as illustrated in Figure VIII-8 which shows scattergrams of the concentrations of Cu, Pb, Zn and Hg versus the grain-size as measured by the percent of the sediment sample finer than 4∅, i.e., percent of silts and clays. All four plots show the same general characteristics of low trace metals concentrations at low silt and clay content and increases at higher percents of fine sediment. In fact, all four metals exhibited very strong correlations between the concentrations of the metals and grain-size for the four samples from the two reference areas (Case Inlet and Port Madison). Linear correlation lines have been plotted for these four samples; all had correlation coefficients better than 0.92. The precision of this correlation seems rather remarkable for data from a natural system and probably results partly from the few samples involved.

Placing subjective but reasonable uncertainty limits of +50 percent around the regression lines for each metal (dashed lines in the figures), to account for analytical and natural variability, encloses many of the values for samples from the industralized embayments. The majority of the remaining samples were near the background levels, even though this data set was specifically biased toward sites near known input sources (Malins et al., 1980).

Very high metal concentrations were almost always associated with the very fine sediments. This is probably explained in part by the coincidental location of strong sources in quiescent areas where fine particulates settle. It would also seem to indicate that metals entering the Sound in more turbulent areas, e.g., via the Metro West Point outfall, are rapidly diluted within the general Puget Sound circulation and do not impart any high local concentrations.
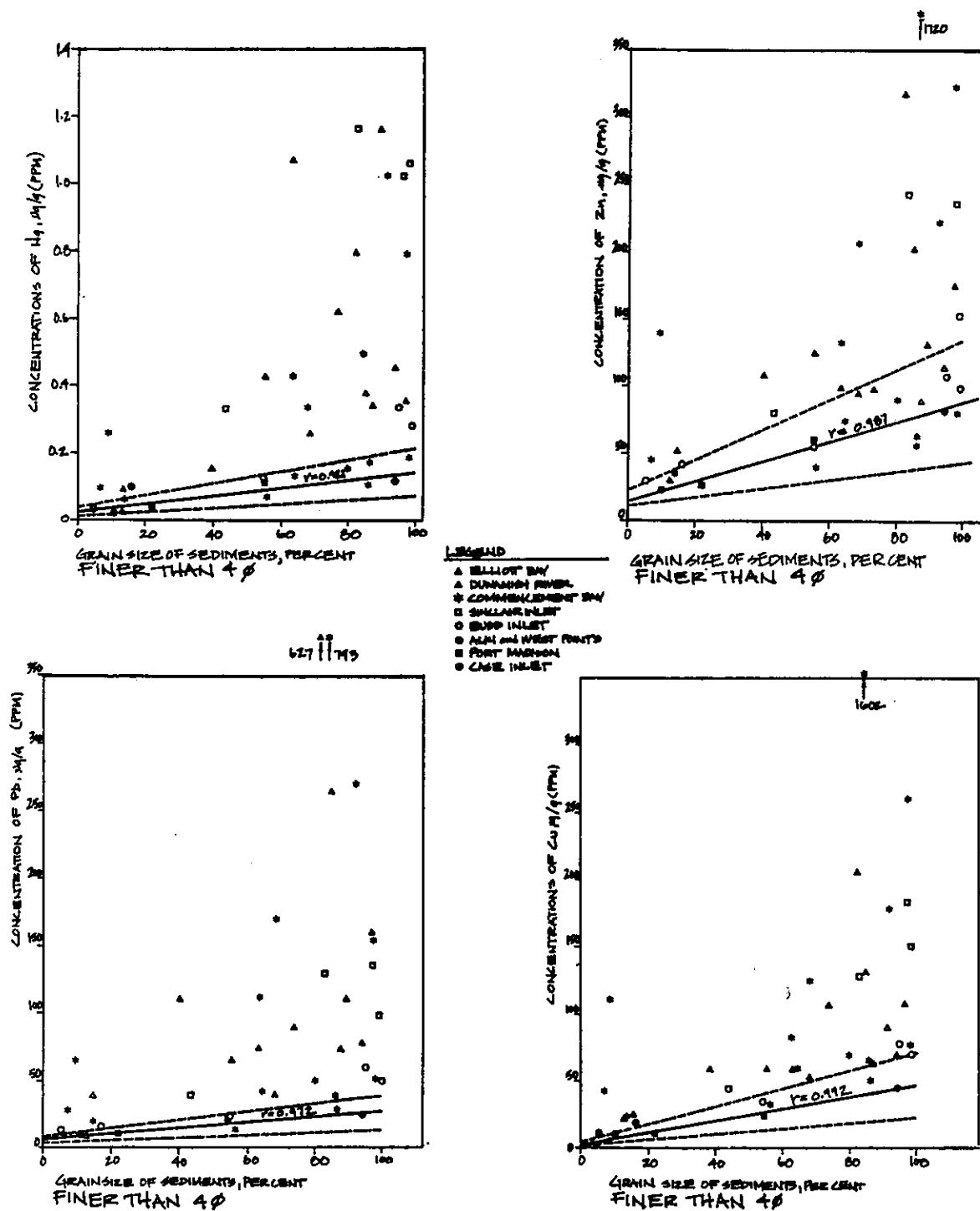
Figure VIII-8. Scatter Plots of the Observed Concentrations of Selected Trace Metals in the Sediments versus the Percent of the Sediment of Grain-size Finer than 4∅. Solid lines represent linear regression correlations for the samples from reference areas (Port Madison and Case Inlet). Dashed lines indicate the range of plus or minus 50 percent of the correlation line.

Data from Malins et al., 1980.

In comparison with the sediments, available data on the relationships of the trace metals and suspended particulates is limited, but still illustrates the point. As noted earlier, the concentrations of trace metals in the suspended particulates have been reported to be at much higher levels than commonly observed in the sediments. However, if the surface sediment concentrations of Cu, Pb, and Zn from the reference areas of the previously discussed study (Malins et al., 1980) are plotted as a function of the fraction of the sediment which is very fine (8$\emptyset$ and finer), the regression line extrapolated to 100 percent (Figure VIII-9) very nearly intersects the suspended matter data reported by Riley et al. (1980). While the strength of the intercomparison between these two data sets is limited by the fact that different extraction and analytical techniques were used, Figure VIII-9 indicates that the concentrations of Cu, Pb, and Zn on most of the suspended particulate samples could be explained on the basis of the fine grain-size of the suspended matter. In addition, the ratios of the concentrations of Cu, Pb, Zn, in the suspended matter (approximately 1:1:2) were essentially the same as observed in the bedded sediments (Figure VIII-8).

One of the major points to be drawn from these plots is that variations in the concentrations of trace metals of at least a factor of two may result solely from differences in the sediment characteristics, and may not reflect contamination of the more concentrated sample. Conversely, a relatively low concentration of trace metals in a coarse sediment matrix may reflect significant local inputs.

Relationship with Particle Matrix

In the sediments there is an apparent correlation between trace metals' concentrations and the organic matter content of the sediments. This was observed for As and Sb and to a lesser extent for Hg and Fe by Crecelius et al. (1975) in sediments from non-polluted areas. Scattergrams of the NMFS data for Pb and Hg (Malins et al., 1980), shown in Figure VIII-10, in general tend to agree with this assessment. Since organic matter and grain-size tend to co-vary, it is difficult to resolve the relative importance of each on the basis of these data. Interestingly, in the Elliott Bay samples (Figure VIII-10) a relatively narrow range of organic carbon was observed (0.1 percent to 2.2 percent) and the concentrations of the metals appear to correlate better with grain-size (compare to Figure VIII-8) when the major outliers are disregarded. Conversely, in Commencement Bay, higher levels and a much wider range of organic matter concentrations were observed (0.4 percent to 7 percent). In the latter area, the correlations of Pb and Hg levels appear to be comparable between the fraction of organic matter and with grain-size. On this basis, it appears that both grain size and organic matter have at least some influence.
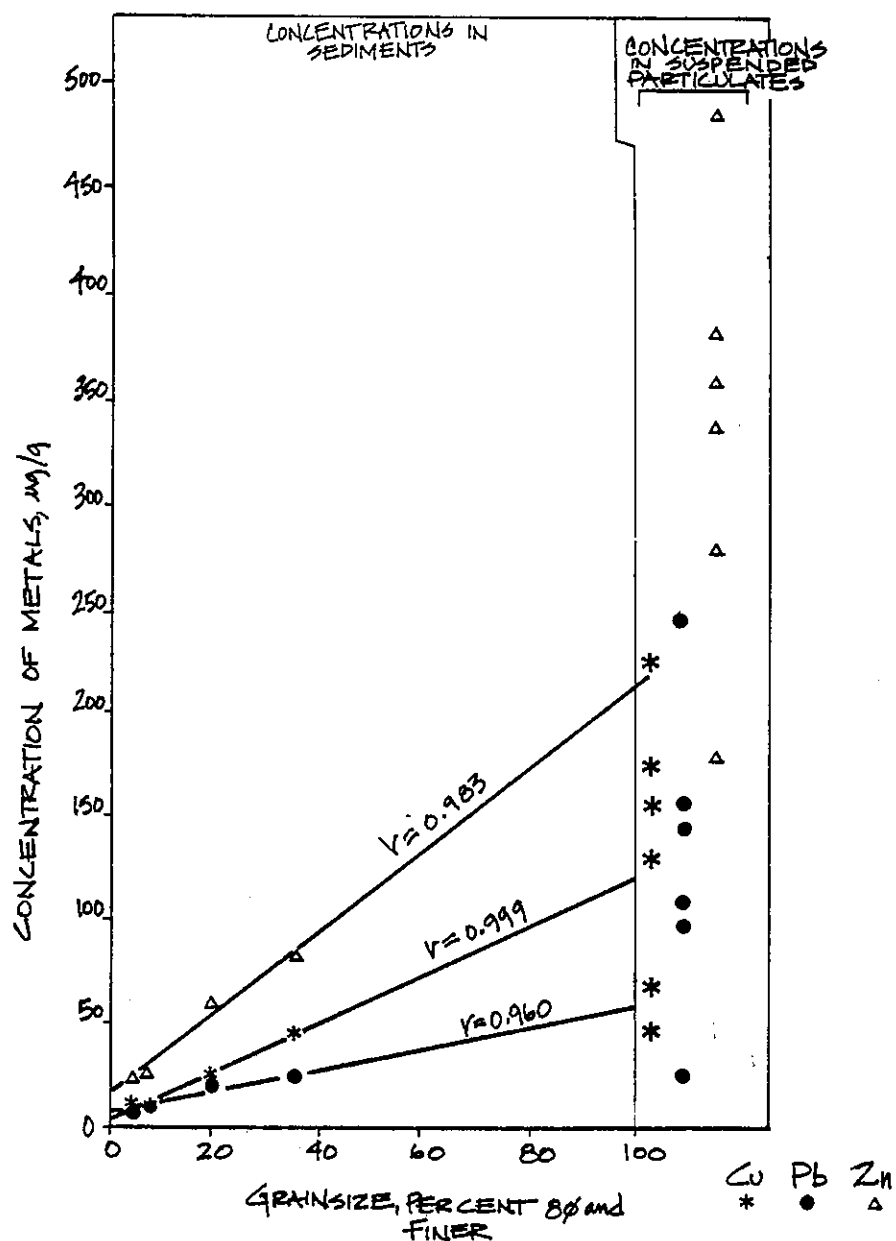
Figure VIII-9. Comparisons of the Extrapolated Correlations of the Concentrations of Selected Trace Metals in the Sediments from Reference Areas (Case Inlet and Port Madison) to the Concentrations Observed in the Suspended Particulate Matter.

Data from Malins et al., 1980 (sediments) and Riley et al., 1980 (particulates).
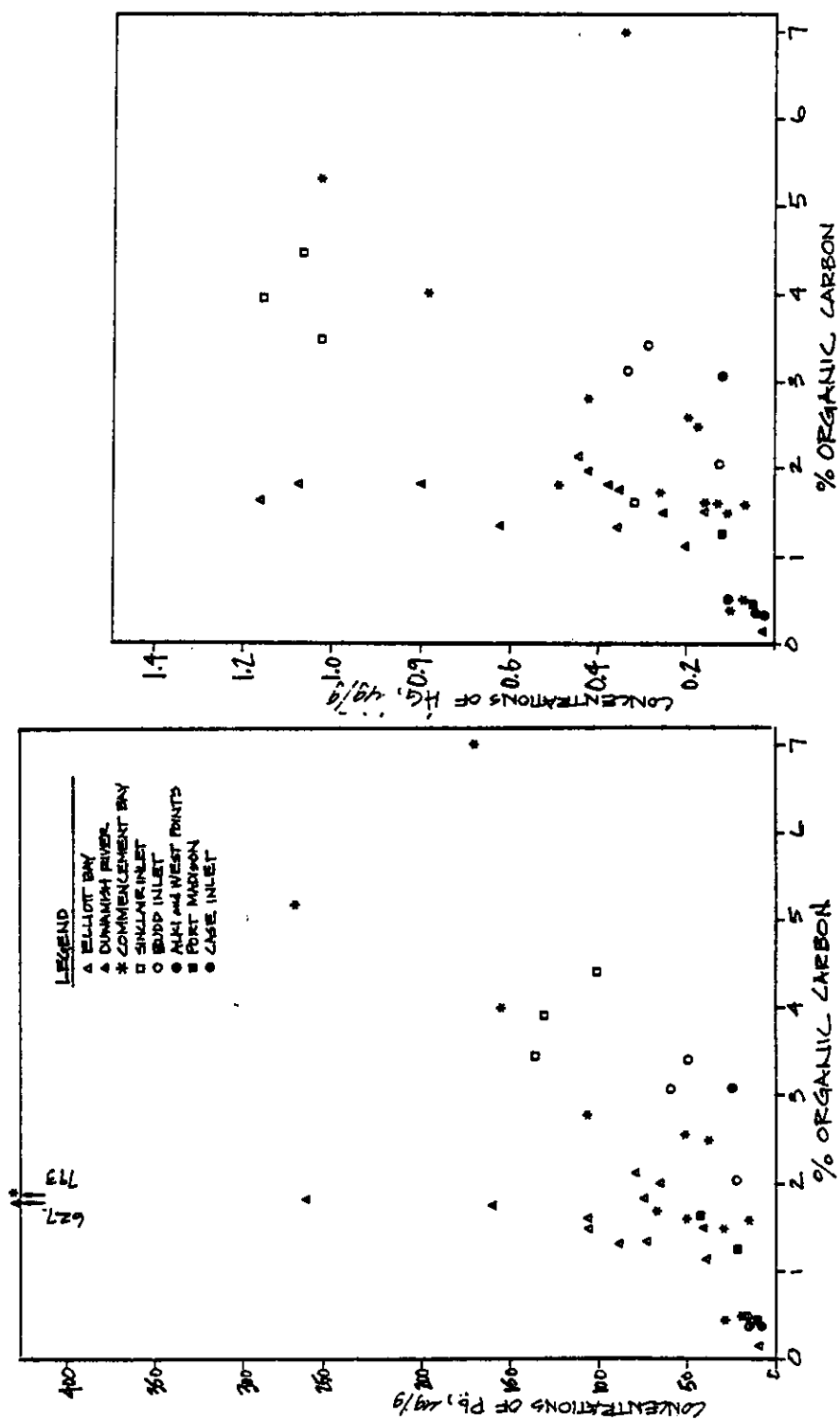
Figure VIII-10. Scattergrams of the Concentrations of Pb and Hg Observed in the Sediments versus the Percent Organic Matter.

Data from Malins et al., 1980.

In the studies of As and Hg reported by Crecelius et al, (1975), it was observed that much of the As (>50 percent) could be removed from non-contaminated sediments by chemical treatments designed to extract Fe and Mn compounds. Only a small fraction (<10 percent) of the As was released by peroxide digestion which oxidizes the sediment organic matter. Conversely, more than 80 percent of the Hg was released by the peroxide digestion and minimal amounts by mineral phase reduction.

The results for As described above appear to be comparable to the behavior of Cu, Pb, and Zn. In another recent study (Blazevich et al., 1977), sediment samples from the Duwamish River were collected during a dredging operation and subjected to serial treatment and extraction to determine the extent of metals' binding to the solid phases. Three samples were collected: one bedded sediment sample from Slip 1, one sample of the solids recovered from the effluent of the pneumatic dredge transfer pipe, and one sample of the solids in the effluent from the second of two settling ponds receiving the dredge effluent. The sampling procedure may have resulted in the fractionation of the sediments so the bed sediment sample contained the highest fraction of coarse material while the final pond effluent would be expected to be primarily the finer material. The concentrations of all metals increased in the order bed sediment <dredge effluent <pond effluent, in agreement with the possible size fractionation. At the same time, no direct size measurements were made and the area dredged was observed to be highly variable in the concentrations of trace metals, particularly Pb and Zn.

The three sediment samples were each subjected to serial extractions in the order ammonium acetate (NH_4OAc), acetic acid (HOAc), hydroxyl amine ($HONH_2$), followed by digestion with hydrogen peroxide (H_2O_2) and nitric acid (HNO_3), and finally by digestion with hydrofluoric acid (HF) and HNO_3.

The results of these extractions are presented in Figure VIII-11 as bar diagrams of the percents of the metals extracted by the steps of the procedure. For simplicity, the amounts extracted by NH_4OAc, HOAc and $HONH_2$ have been combined. For all metals except As, very little release was observed with NH_4OAc, while roughly equal quantities of the metals were released by HOAc and $HONH_2$. For As, negligible releases were observed for any of these treatments except for the pond effluent samples, which responded only to the NH_4OAc.

The first extractions should remove ion-exchangeable and weakly bound metals. Peroxide will destroy the associated organic matter, but in this study, the simultaneous use of HNO_3 probably also resulted in the dissolution of some mineral phases. Hydrofluoric acid and HNO_3 are effective in dissolving the base mineral matrix.
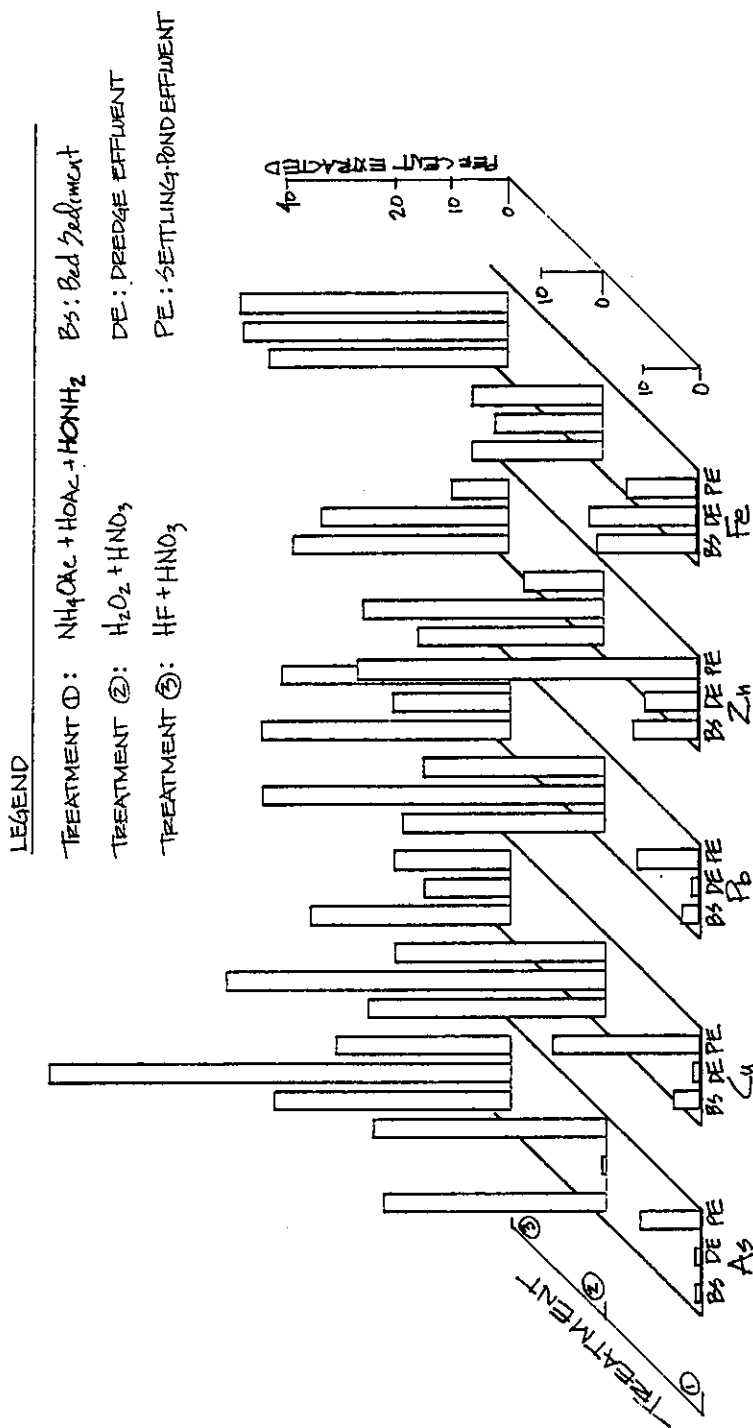
Figure VIII-11. Percentage Recoveries of Selected Trace Metals from Sediments Following Serial Extractions. Methodology Explained in Text.

Data from Blazevich et al., 1977.

In the sediments, Cu, Pb and Zn all show similar behavior. In the bed sediment and the dredge effluent, relatively little of the metals were removed by the weak extractants. Peroxide/HNO_3 treatment removed roughly half of the remaining metals. In the dredge effluent, the H_2O_2/HNO_3 fraction dominated, while the pond effluent sample exhibited a large increase in the weak-acid extractable fraction. For all three sediments, the fraction of weak-acid extractable Zn was larger than for either Cu or Pb.

In comparison, the fractions of Fe were basically unchanged among the sediments, with roughly equal quantities (20 percent to 30 percent) of the Fe in each of the weak-acid and H_2O_2/HNO_3 fractions and the majority (50 percent to 60 percent) recovered after complete digestion. In addition, the trends in the metals fractionation agree with that of exchangeable ammonium (NH_4) which was measured at levels of 47 $\mu g/g$ in the bed sediment, 10 $\mu g/g$ in the dredge effluent, and 122 $\mu g/g$ in the pond effluent. Total NH_4 values for these sediments were not reported.

These data indicate that on the coarser, bedded sediments, most of the metals are associated with mineral phases with a large percentage probably associated with base crystal matrix. In going to finer materials, the fractionation appears to shift toward the more extractable fractions, particularly for Zn.

Since there was relatively poor control over many of the sediment parameters in this study, and since equilibrium may not have been achieved for some processes, e.g., redistribution of metals accompanying transfer from reducing sediments to the well-areated settling ponds, it is not possible to determine whether these results are representative of the majority of Puget Sound sediments.

These data do indicate that Zn is the most reactive of these metals. This is supported by the relatively high levels of dissolved Zn observed in the Sound and the high dissolved to particulate Zn ratios compared to the other metals.

These results can be compared to the relationship of the concentrations of trace metals associated with the suspended matter in the Sound. Based on the data of Riley et al., 1980, graphs were prepared showing the concentrations of Cu, Pb, and Zn as functions of the percents of aluminum (Al), Fe, and organic carbon (Figure VIII-12). These data demonstrate a reasonably strong dependence of all three metals on the mineral phases and a variable but generally inverse relationship to organic matter. Thus, the spatial differences in the concentrations of the metals could be largely explained by the varying levels of mineral phases constituting the particulates. These plots indicate that little if any excess Cu input was occurring, that particulates near Harbor Island and Pier 54 were contaminated with Pb and that only the sample from Pier 54 was contaminated with Zn.
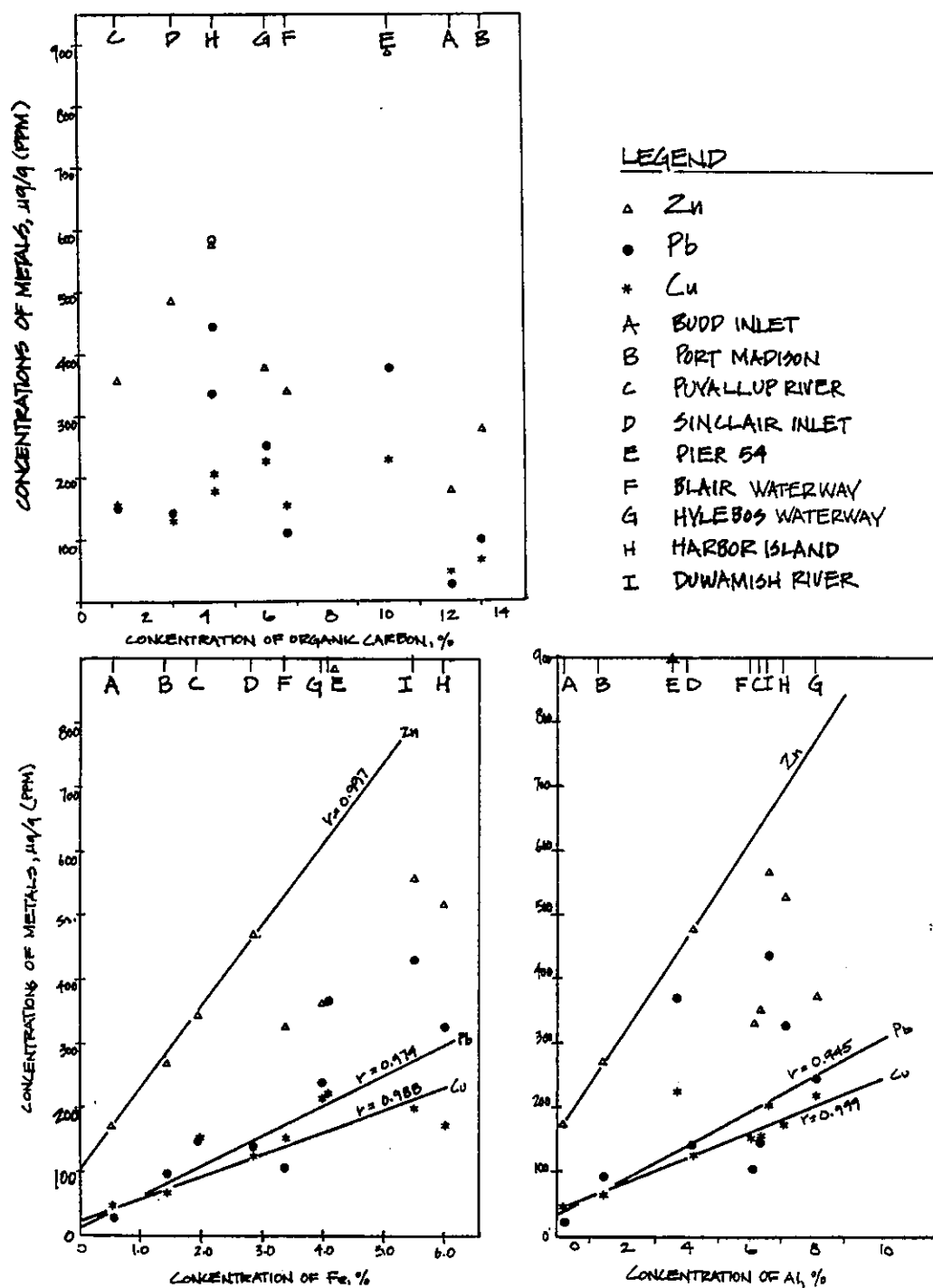
Figure VIII-12. Plots of the Concentrations of Cu, Pb and Zn Observed in the Suspended Particulate Matter versus the Percents of Al, Fe, and Organic Carbon. Solid Lines Represent Linear Correlations for the Three Samples from Budd Inlet, Port Madison, and Sinclair Inlet.

Data from Riley et al., 1980.

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In summary, the foregoing data indicate that As, Cu, Pb and Zn are predominantly associated with the mineral phases in the sediments and particulates. However, it is not clear whether their association is predominantly with the reduceable Fe-Mn oxyhydroxides or with the base crystal matrix. Mercury may be more strongly associated with the organic components of the particulates and sediments. As with the grain-size of the bedded sediments, the above data also demonstrate the dangers in making regional intercomparisons of the contaminant levels based solely on direct comparisons of absolute concentrations.

Exchange of Metals Between Dissolved and Particulate Phases.

The exchange of metals between the dissolved and particulate components may influence the transport and distribution and the availability of the metals for uptake by organisms. This aspect of the chemical relationships has been investigated extensively in other systems (e.g., see Church, 1975; Burton and Liss, 1976), with differing results apparently due to site-specific characteristics. Only two exchange processes in Puget Sound appear to be of possible significance: release and/or sorption of metals by suspended matter within the fresh-saline mixing zones of the river estuaries, and mobilization of metals from sediments.

The former process may be important since it may significantly affect the amounts of metals which enter into the general circulation or are deposited in the river estuary or delta. For example, recent studies of Fe in Puget Sound have shown rapid precipitation of the soluble Fe found in rivers upon mixing with saline water from the Sound. This mechanism was posed as the explanation for the lack of measurable dissolved Fe in the water column and, together with rapid sedimentation, for the lack of major surface excesses of Fe which would be expected if Fe in the rivers mixed conservatively (Murray and Gill, 1978).

Similar studies are currently under way for other metals (Richard Feely, NOAA/PMEL, personal communication), but results were not available when this report was prepared. Data from other studies in the Pacific Northwest provide limited help. Thomas and Grill (1977) observed large increases in the dissolved concentrations of Cu and Zn in the Fraser River plume which were attributed to desorption from riverine suspended matter. However, a second study of the same area documented a nearly three-fold increase in the concentrations of Zn associated with the particulate matter in going from fresh to saline water. In the latter study, this sorbed Zn was associated with an easily extractable (NH_2OH HCl - HOAc) fraction (Grieve and Fletcher, 1977).

In studies in the Columbia River, laboratory exposure to seawater of sediments from fresh water areas resulted in the release of Zn. However, studies in the estuary indicated that particulate Zn mixed conservatively (Duursma, 1976).

Comparing these results with the data presented earlier, the following factors can be considered:

1. Based on very limited data, it could be argued that the average concentrations of Cu, Pb, and Zn (and possibly As) are lower on the riverine particulates than observed in Puget Sound samples (Tables VIII-2 and VIII-4).

2. There is an apparent strong association of Cu, Pb and As with the less labile mineral phases. In the finer particulates, Zn may be associated with a more labile (HOAc extractable) phase.

3. Higher concentrations of Cu, Pb and As in the surface waters have not been observed in Puget Sound. Only limited indications of excess Zn in the surface waters have been obtained.

On the basis of these factors, co-accumulation of Cu, Pb, and possibly As with iron oxyhydroxides appears to be more likely than the release of these metals upon mixing with saline water. The data for Zn are less clear, but overall tend to favor accumulation.

As in the case for the exchange between water-column phases, no direct studies of the behavior of trace metals in the sediments of the Sound have been performed. In this instance, however, the supporting data from other studies is less contradictory. The general process which is of importance is that under reducing conditions in the sediments, the Fe-Mn oxyhydroxides are reduced. Since at least a portion of the metals are associated with this phase, they tend to be released to the interstitial water as well, and may thus diffuse out of the sediments. This process has been documented for Fe in the sediments of Puget Sound with an estimated flux out of the sediment as great as $4.7 \times 10^{-11} g/cm^2 s$. (Murray and Gill, 1978).

In a similar vein, Bothner (1973) noted rapid diffusion of Hg from polluted Bellingham Bay sediments. However, for this metal, a strong association with Fe oxyhydroxides has not been established and the precise mechanism of the mobilization could not be identified. No similar studies have been performed for other metals.

An interesting variation of the basic process outlined above occurs when the strongly reducing zone is at depth below oxidizing sediments. In this case, mobilization and diffusion will occur at depth, but the metals will precipitate in the upper sediment layers, leading to the enrichment of the surface sediments relative to those below. This has

been observed, for example, in an Arctic deep-sea core (Riley and Chester, 1971). It may be important in at least some area of the Sound since Grundmanis and Murray (1977) showed that in cores from the Main Basin, the depth of the anoxic zone was often lower than 40 cm below the sediment-water interface. This process will lead to concentration profiles in the sediments which in many respects will mimic the profiles expected from increasing contamination with time accompanied by no movement of the metals once deposited.

TRANSPORT

The preceding discussions can be summarized within the general transport scenario presented diagrammatically in Figure VIII-13, and discussed below. As noted in the discussions, numerous aspects of the transport in Puget Sound have not been completely elucidated and hence their relative importance cannot be readily established. These areas are indicated by dashed lines in the figure.

Overall, a reasonably simple picture appears to fit the present data. The concentrations of metals in most areas of the Sound reflect advectively transported dissolved and particulate metals originating primarily from natural sources, i.e., rivers, shoreline erosion, and advection of Strait of Juan de Fuca water. Turbulent mixing and recycling at the mixing zones is apparently sufficient to eliminate most spatial differences, either in the water column or in the sediments.

Secondary control over the concentrations of metals in the sediments (and in the suspended particulate matter) results from physical and/or chemical differences in the particulate matter, particularly grain size and percent organic carbon. These differences can generate significant spatial variations in the concentrations of trace metals with higher levels associated with areas of fine grained, organic rich sediments. Within the suspended particulate matter, the inorganic mineral matrix appears to be the major source of trace metals. However, the relative importance of grain size compared to organic carbon is not well established and varies among the metals. In the sediments, fine-grained sediments are usually also richer in organic carbon.

Anthropogenic inputs appear to provide a third level of influence which is important only in limited areas. This influence appears to be expressed in two ways. First, in some areas the source intensity is greater than the ability of the system to dilute the inputs to background levels. Examples of this type of input would include most metals in
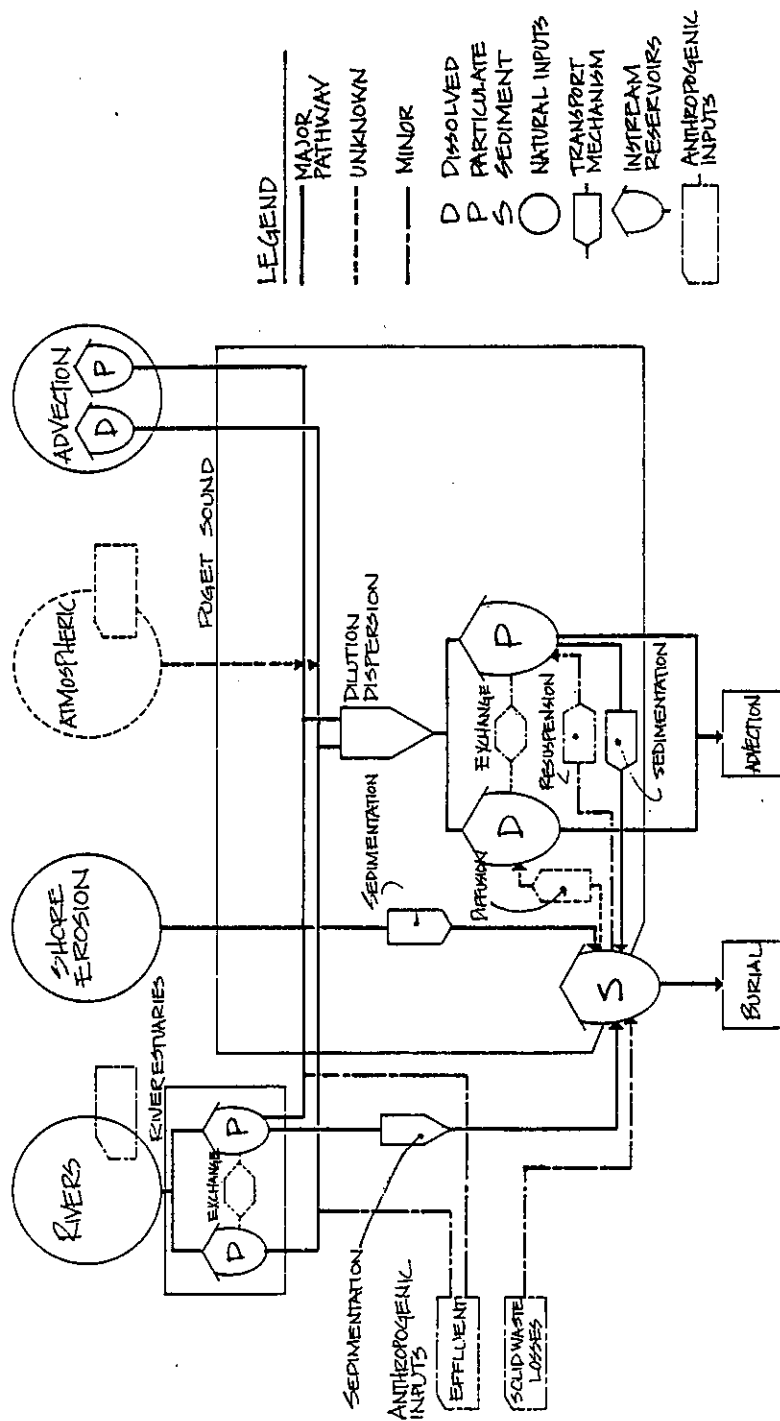
Figure VIII-13. Diagram of Major Transport Pathways for Trace Metals in Puget Sound.

Sinclair Inlet, Pb in Elliott Bay, As (plus Sb) in Quartermaster Harbor and East Passage, and on a much smaller scale, Cu, Pb and Zn near CSOs in Elliott Bay.

Secondly, some areas appear to have received inputs of contaminated solids of relatively low mobility compared to the transport capacity of the immediate receiving system. These areas exhibit very high levels of trace metals within highly localized areas and strong gradients in the concentrations of the metals in the sediments. Such areas have been noted in the waterways of Commencement Bay, in the vicinity of the ASARCO slag discharge, and in the lower Duwamish River.

Overall, anthropogenic inputs appear to have substantially altered the levels of trace metals in Puget Sound only in localized regions.

TEMPORAL TRENDS

As noted earlier, it can be anticipated that recent public concern and regulatory attention should be decreasing the inputs of anthropogenic trace metals to the Sound. However, the data from Puget Sound do not clearly establish any temporal trends.

A few sediment cores were collected in the Sound which exhibited vertical gradients of increasing levels (by about a factor of two) for As (Crecelius et al., 1975), Cu, Pb and Zn (Schell et al., 1976) in more recent sediments. However, these increases were not uniform among all cores taken and were within the range which could result from changes in the grain size of the sediments. In addition, as discussed earlier, the same core profiles might be the result of mobilization of the metals in the deep sediments and precipitation and enrichment in the shallower horizons.

Data from samples in the water column do not indicate any major temporal changes in the concentrations of trace metals associated with the suspended particulates: for example, compare the data in Table VIII-2 from Schell et al. (1977) with those of Riley et al. (1980). Insufficient data are available for comparisons of the dissolved concentrations.

Finally, if as concluded earlier, natural sources dominate the inputs, it is reasonable to assume that no major temporal changes should be seen in the overall levels of trace metals. Rather, elimination of anthropogenic inputs should primarily affect the localized, highly contaminated areas.

ACCUMULATION BY BIOTA

The concentrations of selected trace metals have been measured in a variety of organisms in Puget Sound. Representative data are summarized in Table VIII-9. By and large, the reported concentrations of all metals have been low, showed limited variability among species, and also exhibited limited spatial variability. The latter is consistent with the general distributions of trace metals observed in the sediments and water. This section will examine in more detail the spatial and temporal trends in the distributions of the metals as well as the variations among species and among types of tissue within individual organisms.

It should also be noted that the analysis of trace metals in biological tissue is generally more difficult and prone to error than similar procedures applied to water or sediments. As a result, the caveat expressed at the beginning of this report regarding the inter-comparisons of data from different sources is worth restating at this point. As in the case of the data presented in the preceding sections of this report, an attempt was made to include only those data which appeared to be adequately verified by standardized analytical procedures and agreement in the general results with those of other investigators. In many instances, however, only single values and/or one study were available for many of the biological organisms discussed below.

Spatial Trends

Relatively few of the organisms examined have been studied within a synoptic sampling program. Figure VIII-14 depicts the distribution of the trace metals observed in the edible mussel, Mytilus edulis, the one species which appears to have been examined over the greatest spatial extent. Comparable concentrations were observed for all metals at stations in the Southern Sound and northern Main Basin. These concentrations evidently reflect the response of the mussels to the natural levels of the metals in the Sound.

Among the metals, the concentrations in the mussels decrease in the order Zn>>Cu = Pb>As>>Hg. This trend is similar to that observed in the sediments but the relative enrichment in Zn (roughly 20 times the Cu concentrations) was greater than that reported for the sediments.

Samples in the vicinity of the ASARCO smelter outfall exhibited higher concentrations of all metals, with an apparent gradient decreasing with distance away from the area. This enrichment was particularly striking for Cu. Maximum concentration of 49 μg Cu/g wet tissue were

TABLE VIII-9

CONCENTRATIONS OF SELECTED TRACE METALS
IN THE BIOTA OF PUGET SOUND

TAXA	Concentrations, µg/g wet tissue				
Puget Sound	As	Cu	Pb	Zn	Hg (ng/g)
Bivalves[a,b]	1.0 ± 0.7(32)[g]	3.3 ± 5.7(98)	1.2 ± 0.5(26)	29 ± 28(97)	32 ± 40(95)
Other molluscs[a]	ND[h]	9.1 ± 2.9(3)	1.2 ± 0.5(3)	151 ± 154(3)	ND
Starfish[a]	ND	13 (2)	4.3 (2)	17 (2)	ND
Zooplankton[a,c]	ND	4.4 ± 3.1(6)	1.2 ± 0.6(6)	10.5 ± 6.4(6)	2.5(2)
Shrimp[a,d]	ND	20 ± 8(9)	1.1 (1)	15 ± 4(9)	ND
Crab[a]	ND	14 (2)	2.8 (2)	21 (2)	ND
Octopus[a]	ND	20 (1)	0.8 (1)	85 (1)	ND
Bottom fish[a,b] (muscle)	ND	0.31 ± 0.19(23)	0.5 ± 0.5(3)	6.7 ± 2.8(23)	74 ± 61(23)
Dogfish (Muscle)	ND	2.0 (1)[a]	0.5 (1)[a]	1.4 (1)[a]	970(141)[e]
Roberts Bank, Strait of Juan de Fuca					
Crab[f]	5.2 ± 2.5(20)	9.7 ± 3.2(20)	ND	4.6 ± 8(20)	ND
Bottom fish[f] (muscle)	<0.15	0.8 ± 0.7	ND	9.0 ± 2.1(20)	68 ± 24
Salmon[f]	<0.15	0.5 ± 0.1(3)	ND	8.8 ± 0.9(3)	77 ± 23(3)

a   Data from Schell et al., 1977
b   Data from Price et al., 1978; Cummins et al., 1976.
c   Excluding one set of anomalously high values from the Four Mile Rock dump site.
d   Data from Malins et al., 1980.
e   Data from Hall et al., 1977.
f   Data from EVS, 1979.
g   Mean ± one standard deviation; numbers in parentheses refer to the number of samples constituting the mean.
h   ND indicates no data.
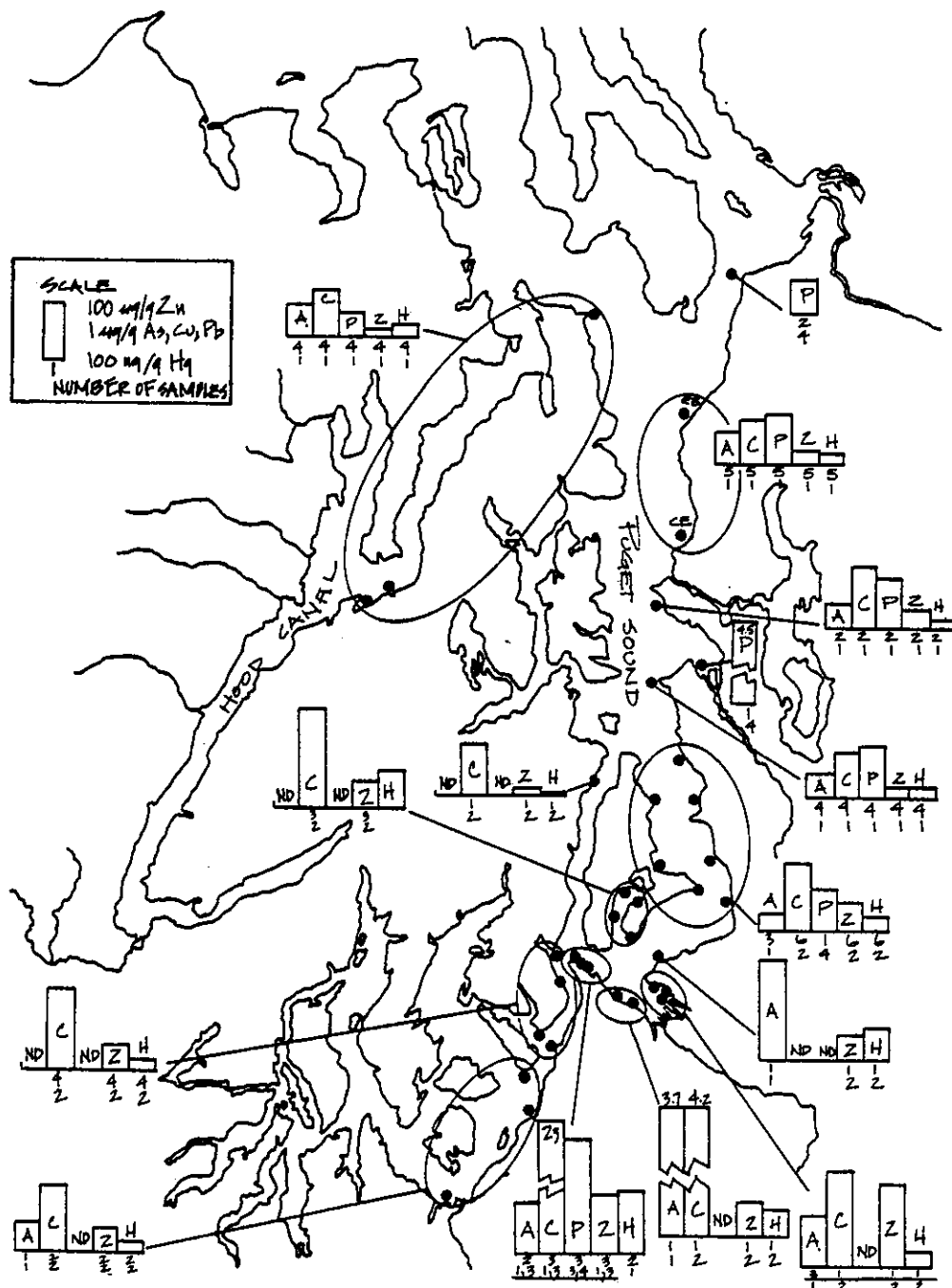
Figure VIII-14. Concentrations of Selected Trace Metals Observed in the Mussel, _Mytilus edulis_, in Regions of Puget Sound.

Data from 1) Schell et al., 1977; 2) Price et al., 1978; 3) WDOE, 1979; 4) Schell and Barnes, 1974.

observed at the ASARCO dock (WDOE, 1979), compared to about 1 μg Cu/g wet tissue at more distant sites. Arsenic, Pb, Zn, and Hg were also enriched but not as strongly as Cu. In addition, the highest levels for these latter metals were not observed at the ASARCO site. Maximum As was observed near Old Tacoma (about 4 μg/g wet tissue); Zn concentrations were greatest near the Hylebos Waterway (160 μg/g wet tissue); and Hg was highest on the southeast side of Vashon Island (220 μg/g wet tissue).

These latter data indicate that the contamination of the mussels may be more pervasive in Commencement Bay and not related solely to the ASARCO discharge. This would agree with the distribution of the metals in the sediments of the area. Unfortunately, only one sample (for Pb in the Duwamish River) has been reported for other areas in which high levels were observed in the sediments (Schell and Barnes, 1974). Similarly, a more limited survey of Hg concentrations in dogfish loin muscles, reported by Hall et al. (1977), indicated higher levels in Elliott and Commencement Bays compared to fish caught in Hood Canal, Port Susan, near Port Townsend and near Blaine (Strait of Georgia). Therefore, while a general correspondence between the concentrations in the organisms and the levels in the sediments appears likely, this relationship cannot be clearly established.

It should also be noted that the majority of the dogfish samples from the Sound exceeded the maximum allowable Hg content for foods marketed in the United States. In Elliott and Commencement Bays, 100 percent and 97 percent of the fish, respectively, exceeded the limit (Hall et al., 1977).

Temporal Trends

No studies of the long-term trends in the concentrations of metals in the biota have been made. Comparisons of the concentrations in shrimp observed prior to 1977 with more recent data indicate slight differences in the metals measured. The differences are probably not significant since different analytical techniques were employed and the samples were not collected from the same areas of the Sound.

Concentrations, μg/g wet tissue

Sampling Time	Cu	Pb	Zn
Prior to 1977[a]	39	1.1	9.2
1979[b]	17 ± 4	<0.5	16 ± 4

a   Schell et al., 1977
b   Malins et al., 1980

On a shorter term, higher concentrations of Zn and Cd were noted in Mytilus edulis and some other molluscs during the summer and fall compared

to the winter and spring (Schell et al., 1977). However, considering the scatter of the data, these differences did not appear to be significant.

In comparison, quite clear increases in the concentrations of Zn and Cu were observed in the brown macroalgae, Fucus sp., during the winter and spring with the lowest levels observed in the fall. The winter concentrations were roughly 3 times those observed in the fall for both metals and at all sampling sites (Schell et al., 1977). Interestingly, this trend would seem to mimic the discharge rates of the rivers and hence may reflect increased levels in the system from this source. It may also, however, reflect seasonal changes in the accumulation of the metals related to changes in the growth rate. Lead showed only minimal seasonal changes (Schell et al., 1977).

Inter-species Differences

As noted in the introduction to this section, the tissue concentrations of trace metals in general show relatively small differences among the different types of organisms (Table VIII-9). However, some inter-species differences were apparent which appeared to be greater than that due to natural variability within the samples of the same organisms.

TABLE VIII-10

COMPARISONS OF THE CONCENTRATIONS OF Cu, Fe, AND Zn
IN THE LIVERS OF ENGLISH SOLE WITH THOSE OBSERVED IN
CRAB HEPATOPANCREAS

	Concentrations, μg/g dry tissue[a]					
	Cu		Fe		Zn	
Location	Sole	Crab	Sole	Crab	Sole	Crab
Budd Inlet	4.9		218		33	
Case Inlet	3.1	223	242	71	28	58
Sinclair Inlet	13	140	385	208	35	69
Duwamish River	3.5	35	661	41	29	28
Hylebos Waterway	8.2	53	509	77	38	49

a   Data from Malins et al., 1980.

While at least some of these differences may be due to analytical problems, major differences can be related to the physiology of the organisms. For example, whole shrimp and crab exhibited relatively high Cu to Zn ratios compared to bottom fish muscle (Table VIII-9), while crab hepatopancreas were similarly enriched in Cu and depleted in iron compared to the concentrations in English sole livers (Table VIII-10). These differences are undoubtedly due to the presence of hemocyanin, a copper-based pigment, in the crustacean blood instead of the hemoglobin found in the fish.

Differences have also been observed in the levels of Zn in Mytilus edulis compared to some other bivalve species (Table VIII-11). The data indicate higher Zn concentrations in Mytilus edulis without comparable enrichment of Cu or Hg. Whether these interspecies differences are the result of specific biochemical variations similar to hemocyanin versus hemoglobin, or whether they result from more general physiological and ecological relationships, e.g., fat content, feeding mode and/or habitat selection, has not been established.

TABLE VIII-11

COMPARISONS OF THE CONCENTRATIONS OF SELECTED TRACE
METALS IN TWO SPECIES OF BIVALVES RELATIVE TO THE
LEVELS IN NATIVE LITTLE NECK CLAMS

| Metal | Concentration Ratios Between Paired Species Organisms | |
	EM/NLN[a,b]	BC/NLN[a,b,c]
As		1.83 (1)
Cu	0.77 ± 0.38 (8/9)[d]	1.73 ± 1.27 (8/11)
Pb		1.20 (1)
Zn	4.01 ± 1.75 (9/9)	1.20 ± 0.71 (7/13)
Hg	1.67 ± 1.76 (5/9)	1.03 ± 0.78 (5/12)

a   EM = edible mussel, Mytilus edulis; NLN = native little neck clam, Protothaca staminea; BC = butterclam, Saxidomus giganteus.
b   Data from Price et al., 1978
c   Data from Cummins et al., 1976
d   Mean of the concentration ratios calculated per site + the standard deviation of the ratios. Number in parentheses indicate the number of pairs showing the ratio trend, e.g., higher (>1) or lower (<1) out of the total number of site pairs. Pairs were established from samples from the same sites analyzed by the same investigators.

One factor which has received some documentation is changes in the observed distribution of metals in the organisms accompanying growth of the organisms. In a recent study of the levels of Hg and Pb in northern squawfish from Lake Washington, Schell and Barnes (1974) report a positive correlation between Hg concentrations in the muscle and the size/age of the fish. The same fish were observed to exhibit a negative correlation between the levels of Pb and the size/age of the fish. A complete explanation for these trends and of the differences in the behavior of the two metals was beyond the scope of the study. In Puget Sound, similar increases in the concentrations of Hg with increasing size of the fish were observed for samples of dogfish loin muscle. In addition, it was observed that male fish had higher Hg concentrations than females of the same size. This sex-related difference was considered to reflect the comparatively slower growth rate of male fish compared to the females (Hall et al., 1977).

Intra-organism Distributions

A few studies have been made which document the variations in the concentrations of metals in different tissues of some fish. Representative data are presented in Table VIII-12, for Cu, Pb, and Zn. The greatest concentrations of Cu in all five species were observed in the livers (excluding the viscera and/or gut contents). In comparison, Pb concentrations were greatest in the bones, while for Zn the levels were more uniform among liver, bone and skin, with the greatest concentrations varying between the liver and the bones. Of some importance for the consumers of fish is that for the three metals studied and for all of the fish species, comparatively low levels were observed in the muscle tissue.

Tissue differences undoubtedly reflect the varying affinities of the tissues for the metals. The metals appear to associate predominantly with enzyme- and/or mineral-rich organs, e.g., the liver and bones, respectively. Obviously, these differences must be kept in mind when comparing the concentrations of metals reported in different studies to insure that a comparable basis for comparison is provided.

The concentrations of trace metals in the biota of Puget Sound have been observed to be generally uniform and low. The data are limited and while apparently supportive of spatial distributions reflecting the levels of contamination in the ambient habitat, e.g., levels in the sediments, they do not fully substantiate this relationship.

Inter-species differences in trace metals levels appear to be less than the variations due to spatial location, except for variations resulting from major physiological differences, e.g., hemocyanin versus hemoglobin.

TABLE VIII-12

COMPARISON OF THE CONCENTRATIONS OF SELECTED TRACE METALS OBSERVED IN INDIVIDUAL ORGANS AND TISSUE OF FIVE SPECIES OF FISH

		Concentrations of Metals, μg/g Tissue				
	Organism	Muscle	Liver	Skin	Bone	Viscera & Contents
I.	COPPER					
	English Sole[a]	0.19	6.0	0.66	0.89	3.5
	Dover Sole[a]	0.11	5.8	1.06	0.92	6.1
	Dog Fish[a]	1.96	2.6	0.74	1.6	7.3
	Copper Rockfish[b]	3.4	9.3	ND[c]	ND	2.4[d]
	Pile Perch[b]	3.7	24.0	ND	ND	54.0[d]
II.	LEAD					
	English Sole[a]	0.21	0.55	0.78	4.1	1.5
	Dover Sole[a]	0.18	1.4	1.05	3.6	1.7
	Dog Fish[a]	0.54	0.02	1.8	6.4	2.5
	Copper Rockfish[b]	2.5	<2.5	ND	ND	3.0[d]
	Pile Perch[b]	<2.5	3.8	ND	ND	5.8[d]
III.	ZINC					
	English Sole[a]	3.7	31.3	19.9	10.6	8.1
	Dover Sole[a]	3.3	20.8	8.9	12.8	32.1
	Dog Fish[a]	1.4	5.9	6.46	13.0	4.3
	Copper Rockfish[b]	5.1	26	ND	ND	20[d]
	Pile Perch[b]	8.8	48	ND	ND	80[d]

a Data from Schell et al., 1976.
b Data from WDOE, 1979; samples from near the ASARCO outfalls.
c ND indicates no data.
d Gut contents only.

SUMMARY

Probably the most fundamental conclusion which can be drawn from the studies of the concentrations of the trace metals in the water column, sediment and biota is that, in general, the levels of all metals are at or near natural concentrations in most regions of Puget Sound. Obvious exceptions to this general trend have been observed, however, with concentration of metals in the sediments and, to a lesser extent, in the biota near areas of extensive industrial development. Elliott and Commencement Bays and Sinclair Inlet all had varied concentrations of arsenic, copper, lead, mercury, and zinc, primarily in limited areas close to shore-based industries, e.g., the ASARCO smelter in Commencement Bay and the shipyards and secondary lead smelter in Elliott Bay. More widespread contamination within these embayments, but at much lower levels than the maximums, was also noted in the sediments for lead in Elliott Bay and for mercury in Sinclair Inlet.

These trends appear to reflect the overall dominance of natural inputs, e.g., riverine transport, and shore-erosion, over anthropogenic sources. The data indicates that only in proximity to sources, particularly in poorly flushed areas, do the inputs greatly exceed the capacity of the system to assimilate and dilute the trace metals. Although limited, the concentrations of trace metals in the biota resident to the Sound by and large appear to correspond to the spatial distributions observed in the sediments: highest tissue levels were observed in areas of high concentrations in the sediments. The levels observed in the organisms reflect both the natural uptake of the metals, many of which are essential nutrients, leading to some differences in the relative concentrations of different metals among different species, and a response to the absolute levels in the ambient environment. However, no systematic study of the modes or rates of intake of the metals has been performed in Puget Sound.

In general, the concentrations of trace metals in the biota which have been reported to date are low. As discussed more fully in Chapter 10, no toxic response of any organism to trace metals in the Sound has been identified. The hazard to consumers of organisms from the Sound also appears to be low, with the exception that mercury levels in resident dogfish meat have been reported to generally exceed the Food and Drug Administration maximum allowable levels for human consumption. Considering the limited sampling of biota for metals, particularly in the more contaminated areas, it should be noted that the possibility exists that the concentrations of mercury and other metals may also exceed recommended human dietary limitations in other organisms, at least in limited areas such as the waterways of Commencement Bay and in the lower Duwamish River.

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CHAPTER 9. ORGANIC CONTAMINANTS

While considerable quantities of organic matter of biogenic origin are natural components of all ecosystems, the compounds considered in this section are principally of anthropogenic origin either due to very limited natural production or because the compounds are totally man-made. Many of these compounds are toxic. Table IX-1 lists compounds and classes of compounds which have been identified to date in the water, sediment, or biota of Puget Sound, in tributary waterways and/or in effluents discharging to the Sound. Three groups of these compounds of toxicological concern have received the most study in the Sound:

1. Polychlorinated biphenyls (PCBs). These compounds are chemically similar to some of the chlorinated pesticides and represent a classic case of an industrial compound becoming an environmental threat through careless and unknowing handling and disposal.

2. Other chlorinated industrial compounds. Recent studies (Malins et al., 1980; Riley et al., 1980) have demonstrated the presence in the Sound of a large number of chlorinated organic compounds apparently originating from the disposal of industrial waste products or by-products. Only a few of these compounds have been identified, including some volatile chlorinated compounds, e.g., dichloromethane, trichloroethylene, and tetrachloroethylene; chlorinated benzenes; chlorinated aromatic hydrocarbons; and chlorinated butadienes. Most of the available data concerns specifically the latter groups and for simplicity the discussions which follow will refer primarily to the characteristics of the chlorinated butadienes (CBDs) as one of the most prevalent components and representative of this class of compounds.

3. Arenes. The arenes consist of a large number of multi-ring aromatic hydrocarbons. These compounds are of particular concern because at least some of the compounds in this group are known to be mutagenic and carcinogenic, e.g., benzo(a)pyrene (Kraybill et al., 1977). Two principal sources of arenes are currently recognized. They constitute a minor fraction of petroleum products and are also generated in the combustion of organic fuels (Laflamme and Hites, 1978). Only a few of the many compounds have been positively identified and surveyed in the Sound. Major examples are listed in Table IX-2.

TABLE IX-1

ORGANIC COMPOUNDS AND CLASSES OF COMPOUNDS WHICH HAVE BEEN
IDENTIFIED IN THE WATER, SEDIMENT, OR BIOTA OF PUGET
SOUND, TRIBUTARY RIVERS, OR EFFLUENT DISCHARGES

Compound	Water		Sediment		Biota		Effluent[a]
	Marine	Riverine	Marine	Riverine	Marine	Riverine	
Aliphatic hydrocarbon[b] (paraffins)	+	+	+	+	+	+	M (P,I)
Aromatic hydrocarbon[b] (arenes)	+	+	+	+	+	+	M (P,I)
Halogenated aliphatics[c]							
halo-methanes, ethanes, propanes		+		+		+	M,P (I)
chlorobatudienes	+		+		+		M,I
Halogenated aromatics							
chlorobenzenes (mono-hexa)	+		+		+		M
other chloroaromatics[d]			+				
PCBs and Pesticides							
PCBs (di-nona)	+	+	+	+	+	+	M,P
DDT and metabolites	+	+	+	+	+	+	M,P
endosulfan		+					
isophorone		+		+			M
hexachlorocyclohexane			+		+		M
aldrin			+				
chlordane			+		+		
nonachlor			+		+		
heptachlor			+				
Phthalate Esters							
bis (2-ethylhexyl)		+				+	M
diethyl						+	M
di-n-butyl				+		+	M
di-n-octyl						+	
dimethyl						+	
butyl benzyl							M
Ethers							
2-chloroethylvinyl						+	
bis (chloromethyl)						+	
bis (2-chloroethyl)							M
bis (2-chloroisopropyl)							M
Phenolics							
phenol		+		+			M
dimethylphenol							M
2,4,6-trichlorophenol						+	M
pentachlorophenol						+	M,P
cresol							M
p-chloro-m-cresol						+	
(phenolics)[e]	+						P
Other Compounds							
azobenzene (from di-phenylhydrazine)							M
2,6-dinitrotoluene							M
n-nitrosodimethylamine							M
n-nitrosodi-n-propylamine							M
chlorinated dibenzofurans			+				

a   Letter notation refers to municipal (M), pulp and paper (P), and other industrial (I)
    discharges. Sources identified in parentheses are assumed to be discharging the
    materials due to their ubiquitous distribution. No actual measurements were found.

b   Both hydrocarbon groups contain many compunds which occur together in complex and
    variable mixtures.

c   The volatile halogenated aliphatics also generally occur as a complex and variable
    mixture of compunds resulting primarily from the uncontrolled reactions occurring
    during the disinfection of drinking water and wastes. More than 24 compunds have
    been identified in Puget Sound samples.

d   More than 20 of these compounds have been identified, apparently part of a large
    group of chlorinated organic compounds probably also originating from the chlori-
    nation of wastes.

e   Measured by nonspecific test to determine phenolic constituents.

Sources: Malin et al., 1980; Riley et al., 1980; City of Tacoma, 1979; METRO, 1979;
          D. Tangarone, Region X, U.S. EPA, unpublished data, 1980.

TABLE IX-2

ARENE COMPOUNDS WHICH HAVE[a]
BEEN SURVEYED IN PUGET SOUND

1-to-2 Ring Compounds	3-to-5 Ring Compounds
isopropylbenzene	phenanthrene
n-propylbenzene	anthracene
indan	fluoranthene
naphthalene	pyrene
benzothiophene	benz(a)anthracene
1-methylnaphthalene	chrysene
2-methylnaphthalene	benzofluoranthenes
2,6-dimethylnaphthalene	benzo(e)pyrene
biphenyl	benzo(a)pyrene
acenaphthylene	perylene
acenaphthene	indeno(1,2,3-cd)pyrene
flourene	
dibenzothiophene	

a   From Malins et al., 1980; Riley et al., 1980; Carpenter and Fairhall, 1979; this listing is not exhaustive of all compounds present but includes those which have been positively identified.

In addition to the above compounds, relatively low levels of some chlorinated hydrocarbon pesticides have been observed, including DDT and its metabolites, lindane, chlordane, nonachlor, aldrin, and heptachlor (Pavlou et al., 1973; Malins et al., 1980). The levels of all of these compounds are generally much lower than those of the other constituents, e.g., DDT and its metabolites have generally been observed at levels of 10 percent or less of the PCBs, probably reflecting limited agricultural use in the Puget Sound region. Because of these low levels, and a paucity of data, limited consideration of these compounds will be given in this report.

It should be emphasized, however, that at the present time, research in the area of organic contaminants has been limited by the available analytical methodology to relatively few of the many possible compounds which may be present. In particular, it is important to note that the data are limited primarily to low polarity, relatively non-reactive compounds. The limitations raise the obvious possibility that many other potentially hazardous compounds are present. Examples might include oxygenated hydrocarbon analogs including phenols, quinones, and organic acids as both the parent compounds and as the chlorinated derivatives (Burlingham et al., 1976), and fatty acids and resins from wood products and pulp mill wastes (Rogers and Keith, 1976; Fox, 1976).

It is also necessary to make one other qualification to the information presented in this report. That is, the data presented, particularly for the PCBs, represent the summary of a number of years of research extending from the early 1970s. During this time regulatory efforts have been made to eliminate the discharges of these and other hazardous materials. As a result, some of the data may include historical values which are no longer representative of the present conditions in the Sound. To the extent possible, temporally dependent data will be acknowledged.

The temporal factor is particularly important regarding the interpretation of levels of contaminants observed in the sediments. Most of the compounds under consideration are reasonably stable in the sediments (see discussions below) and the normal sampling methods generally result in the collection of a sample representing the multi-year deposition of sediment. Thus these samples provide a time integrated measure of the contaminant inputs, but they may also not be representative of current input rates.

DISTRIBUTION IN SEDIMENTS

Since the compounds of interest to this report accumulate in the sediments, this phase of the system provides a convenient matrix for examining the comparative levels of contamination in the various sub-regions of the Sound.

Overall Distribution

The concentrations of total PCBs, total CBDs, and total arenes (i.e., sum of measured arenes, Table IX-2) are summarized in Figure IX-1. The general distributions agree with those of the trace metals, i.e., relatively low levels of the organic contaminants in non-urban areas with much higher levels in sediments from developed regions. It should be noted, however, that at least low levels of the compounds have been detected in all areas of the Sound and in the Strait of Juan de
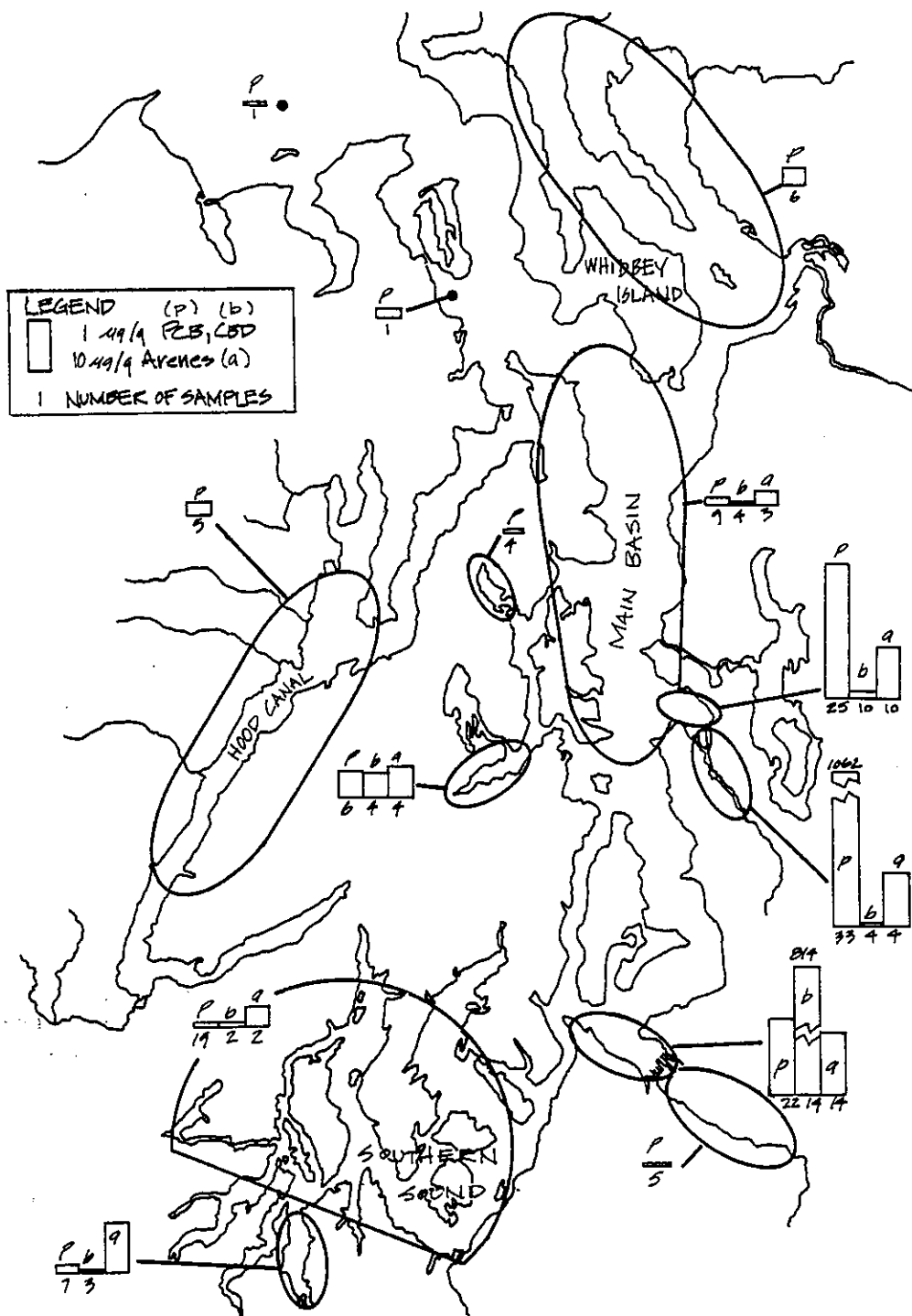
Figure IX-1. Averaged Concentrations of PCBs, CBDs, and Arenes Observed in the Sediments of Regions of Puget Sound. For data sources, see regional figures (Figures IX-2 through IX-8).

Fuca (PCBs and arenes). The widespread distribution probably reflects the long history of inputs of these materials, the rapid and complete mixing of waters in Puget Sound, and their persistence in the marine environment.

For purposes of this discussion, the lower concentrations observed in the non-urbanized areas of the Sound provided the reference levels for the spatial intercomparisons. As such, they are referred to as "background" levels. However, it must be emphasized that the PCBs and CBDs (and many of the other compounds listed in Table IX-1) are xeno-biotics whose true background concentration is zero. There are possible natural sources for the arenes.

Distribution in Embayments

In general the trends in the levels of organic contaminants in the embayments follow those of the trace metals. In particular, the data indicate that, to a large extent, the high regional means result from a few very high values apparently associated with localized sources. These data are discussed below. The reader should note that the scales on the figures were varied to ensure adequate resolution of trends within the different subregions.

Budd Inlet. The concentrations of PCBs, CBDs, and arenes in Budd Inlet and the Southern Sound are presented in Figure IX-2. The concentrations of PCBs and arenes observed in the mid-inlet sediments of Budd Inlet appeared elevated in comparison to the background sediments from undeveloped areas of the Southern Sound.

PCBs showed the greatest enrichment, roughly a factor of 10, and also a trend of increasing concentrations toward the head of the inlet. However, in comparison with PCB levels in most areas of the Main Basin and its tributary embayments (e.g., Hood Canal and Whidbey Basin), the concentrations in Budd Inlet, and the Southern Sound, in general, were low.

The arenes were elevated by about a factor of two compared to the levels in Case Inlet. This difference may not be significant, but rather may result from differences in the sediment characteristics. CBDs were observed at background levels in Budd Inlet.

Sinclair Inlet. The concentrations of PCBs, CBDs, and arenes are presented in Figure IX-3 for Sinclair Inlet and the surrounding areas. The levels of all of the contaminants in the Port Orchard system away from Sinclair Inlet were low and appeared to be representative of the background levels in the Main Basin. Within the inlet, the concentrations of all of three groups of compounds were observed at levels from 10 to 100 times greater than in the non-urbanized areas. The highest
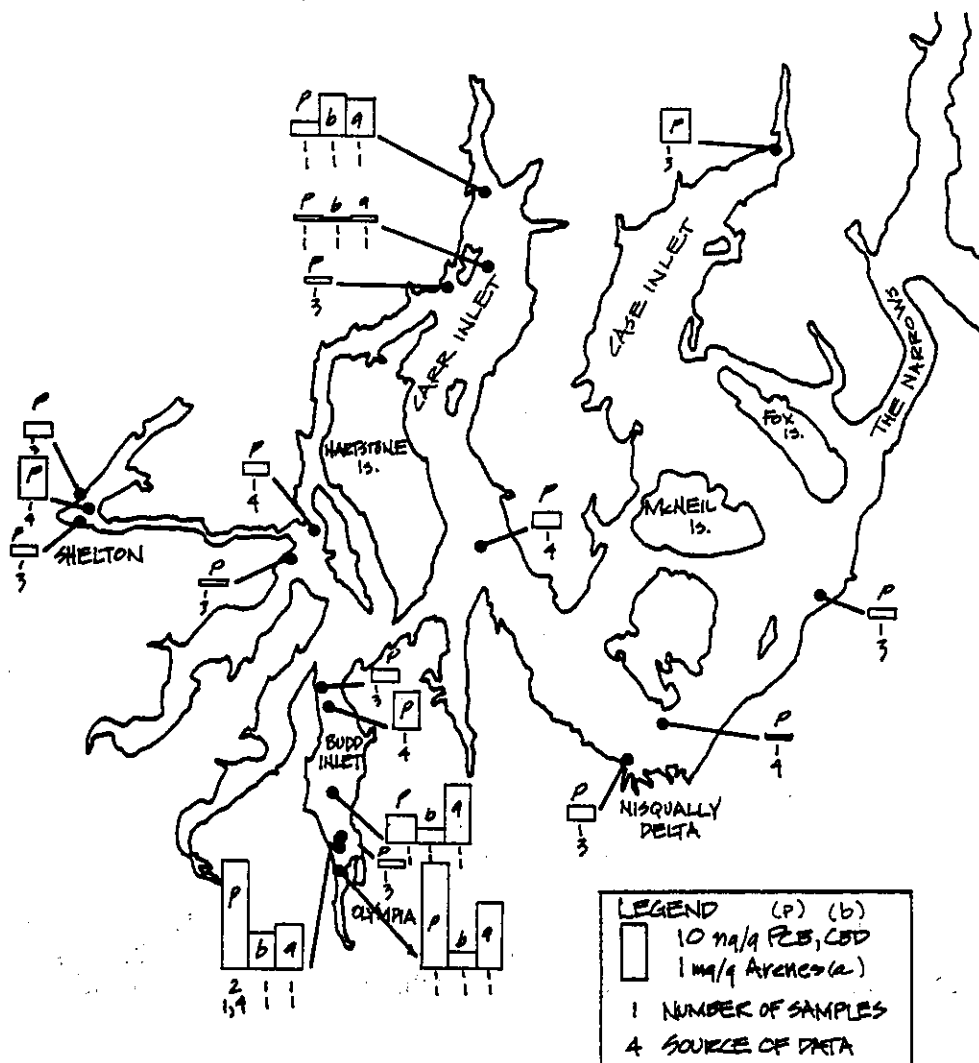
Figure IX-2. Concentrations of PCBs, CBDs and Arenes Observed in the Sediments of Budd Inlet and Other Areas of the Southern Sound.

Data from 1) Malins et al., 1980; 3) Mowrer et al., 1977; 4) Pavlou et al., 1977.
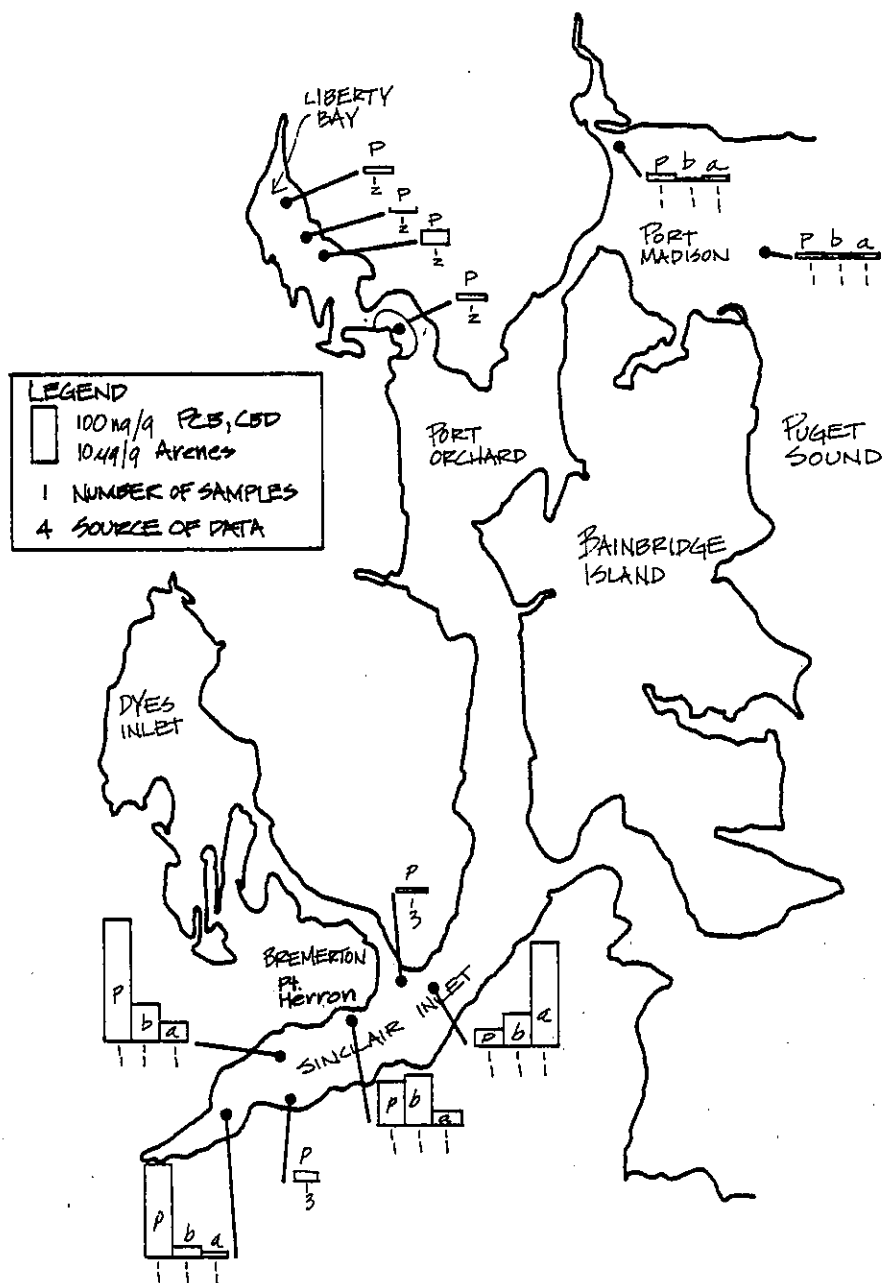
Figure IX-3. Concentrations of PCBs, CBDs, and Arenes Observed in the Sediments of Sinclair Inlet and Other Areas of the Port Orchard System.

Data from 1) Malins et al., 1980; 2) Cummins et al., 1976; 3) Mowrer et al., 1977.

levels of PCBs (218 ng/g) and CBDs (90 ng/g) were observed near the
Bremerton Harbor. PCBs and CBDs both appeared to decrease away from
this area. The highest concentration of total arenes (18 µg/g) was
noted at the station south of Port Herron, while stations from the head
of the inlet indicated relatively uniform concentrations at nearly an
order of magnitude lower levels.

As was noted for the trace metals' data, these distributions
indicate that, while the input sources are probably localized in the
Bremerton harbor area, the slow flushing has resulted in the accumu-
lation and sedimentation of relatively high levels of organic con-
taminants throughout Sinclair Inlet.

Commencement Bay. The concentrations of PCBs, CBDs and arenes
in the surface sediments of Commencement Bay are presented in Figure IX-4.
Again, the general characteristics of the distribution are similar to
those observed for the trace metals. The majority of the stations
sampled exhibited relatively low contaminant levels for PCBs and arenes,
being generally within an order of magnitude of the background levels.
At a few stations, particularly in the Hylebos and City Waterways, very
high concentrations (2 to 3 orders of magnitude above background) were
observed.

In addition, for the PCBs, comparisons of the relative concen-
trations of the chlorobiphenyl components of different degrees of
chlorination indicate that the types of PCBs associated in the sediments
vary as well as the concentrations. For example, tetrachlorobiphenyls
contributed the greatest fraction (25 percent) of the PCBs at a station
off Old Tacoma while hexachlorobiphenyls (38 percent) dominated in the
Hylebos turning basin (Malins et al., 1980). These differences in the
constituency of the PCB residues may reflect in part fractionation
during transport and accumulation, but more likely indicate different
PCBs and hence, by implication, different sources for the residues.
Similar variability in the relative concentrations of individual arenes
and CBDs were not apparent.

The CBDs exhibited spatial variability similar to the PCBs and
arenes. However, the average concentrations observed at all stations
were roughly an order of magnitude above background. These elevated
levels are similar to those observed in Sinclair Inlet. One extreme
value for the CBD (9000 ng/g) was observed at the station near Old
Tacoma in the southwestern bay, but subsequent sampling in the same
area found much lower values indicating patchiness similar to that
observed in the PCB and arene distributions (Malins et al., 1980).

Elliott Bay. The observed distributions of PCBs, CBDs and arenes
in Elliott Bay are presented in Figure IX-5. The general trends
in the surface concentrations indicated higher levels in the southeastern
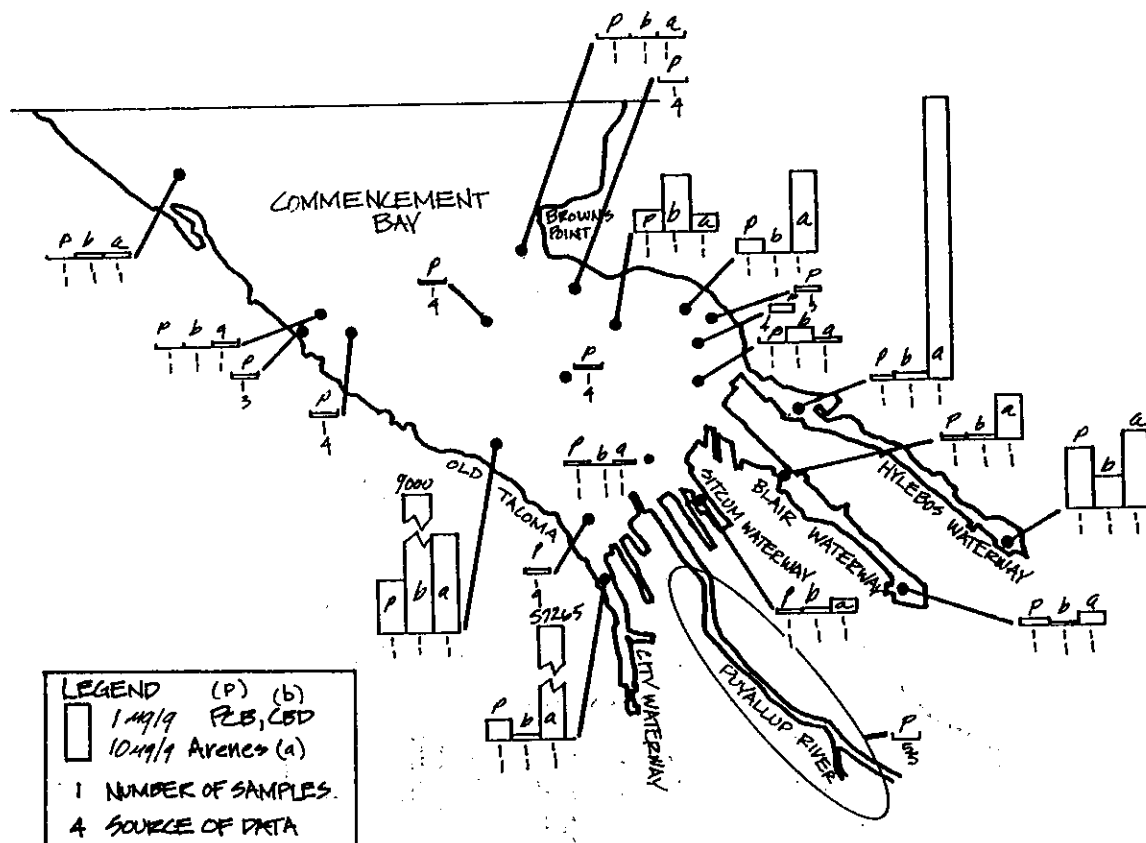
Figure IX-4. Concentrations of PCBs, CBDs, and Arenes Observed in the
Sediments of Commencement Bay.

Data from Malins et al., 1980; 3) Mowrer et al., 1977; 4) Pavlou et al.,
1977; 5) Finger et al., 1978.
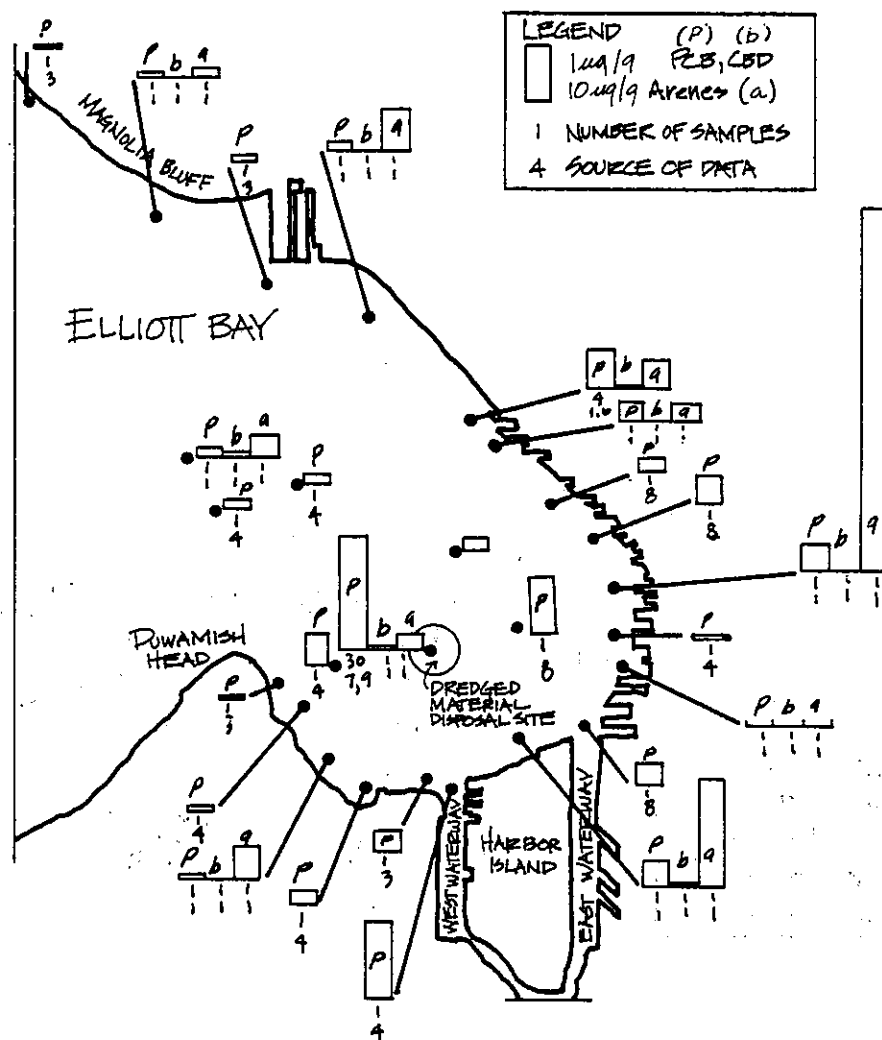
Figure IX-5. Concentrations of PCBs, CBDs, and Arenes Observed in the
     Sediments of Elliott Bay.

Data from 1) Malins et al., 1980; 3) Mowrer et al., 1977; Pavlou et al.,
     1977; 6) Tomlinson et al., 1976; 7) Pavlou et al., 1978; 8) Hom, 1978.

bay and along the Seattle waterfront. For PCBs, high values were also associated with a dredged-material disposal site in the south central bay. As was the case in Commencement Bay, however, the data showed considerable spatial variability.

The variability is further illustrated in Figure IX-6, which presents data for PCBs in a number of samples from the southern bay. These data indicate that while there was a general trend in the surface sediments of high values in the eastern bay grading to lower levels to the west, large differences in concentration, at least as great as an order of magnitude, were observed between closely spaced stations. Similar variability was noted in profiles of the concentrations of PCBs in cores from the same area (Figure IX-7). While demonstrating a general decrease with depth, probably reflecting the historical usage of PCBs, variability of at least a factor of two between small depth intervals was reported. These large concentration changes were often accompanied by marked changes in the relative concentrations of the PCB components.

Whether such high spatial inhomogeneity is characteristic of the CBDs and arenes has not been fully established due to more limited samplings of these latter compounds. The large differences among stations, illustrated in Figure IX-5, argues for such variability.

Duwamish River. In comparison to the trace metals, data for organic contaminants in the Duwamish River are limited (Figure IX-8). In addition, two studies which performed intensive sampling for PCBs examined limited portions of the river which were subsequently dredged and hence do not provide information on recent conditions (Blazevich et al., 1977; Pavlou et al., 1978). The data indicate that the entire navigable channel has been quite highly contaminated with PCBs with higher levels observed in the east and west waterways. The limited data do not allow for generalizations regarding CBDs and arenes.

The data also show that very high levels of PCBs have existed in the upper portion of the estuary, an area not observed to be enriched in trace metals. As with the trace metals, however, the intensive sampling illustrates both the small scale variability in residue levels and the apparent limited transport from the source area.

DISTRIBUTION IN THE WATER COLUMN

Studies of the concentrations of PCBs, CBDs and arenes in the water column are limited. Due to their low solubility and tendency to accumulate on particulate phases, the concentrations can be expected to be very low. Only one recent study has examined the levels of trace

Figure IX-6. Concentrations of PCBs Observed in the Sediments of Southern
Elliott Bay. Dashed Square Indicates the Location of a PCB-Contaminated
Dredged-Material Mound.

Data from Dexter et al., 1979.
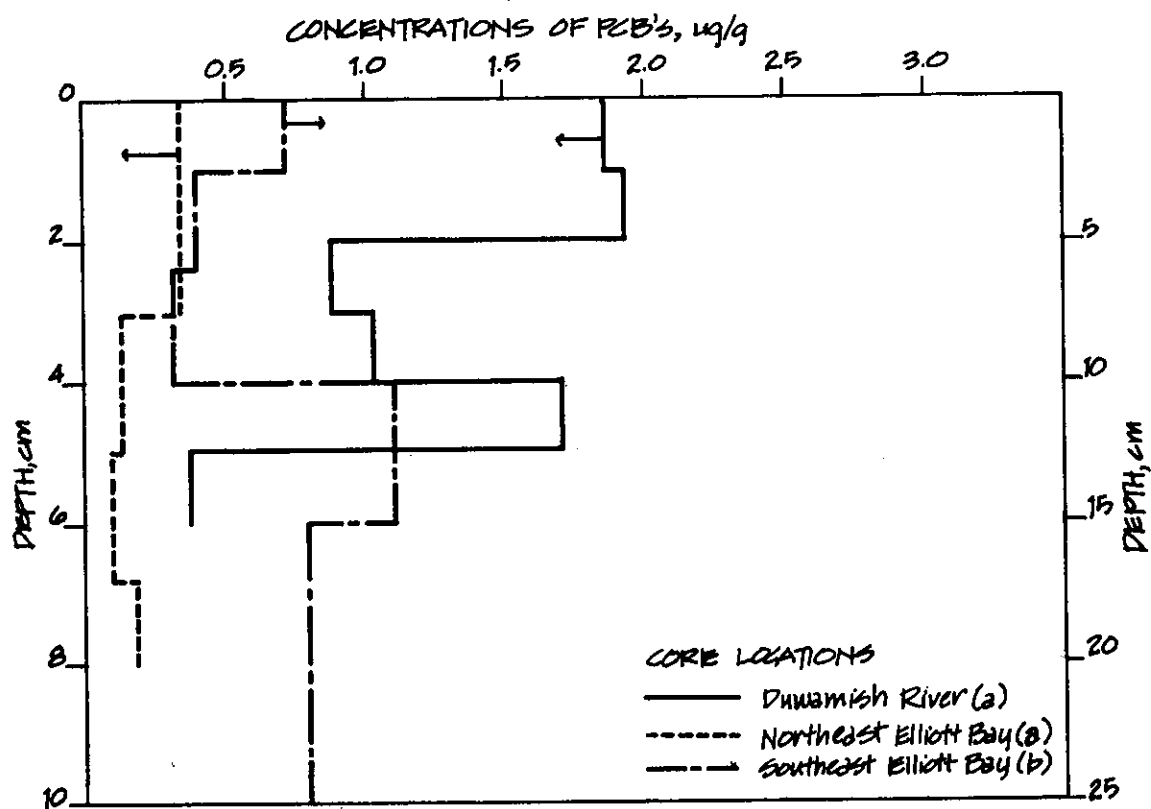
Figure IX-7. Concentrations of PCBs Observed in the Sediments of Cores from Elliott Bay and the Duwamish River.

Data from a) Hom, 1978; b) Dexter et al., 1979.
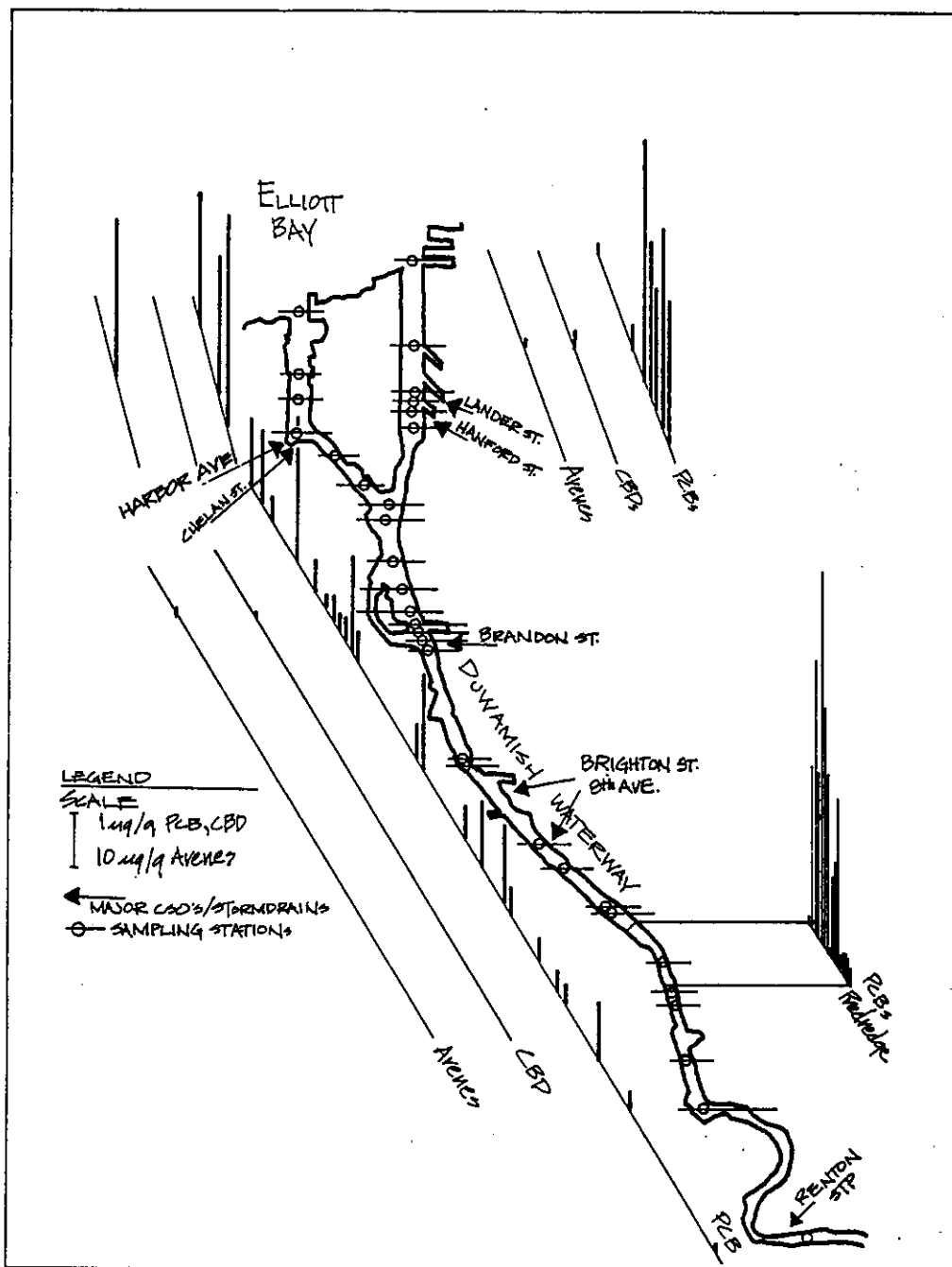
Figure IX-8. Concentrations of PCBs, CBDs, and Arenes Observed in the
    Sediments of the Duwamish River. Inset presents data for area which was
    dredged and dumped into southern Elliott Bay in 1976. Approximate
    locations of major CSOs, storm drains, and the Renton STP are indicated
    by arrows.

Data from Blazevich, 1973; Tomlinson et al., 1976; Blazevich
    et al., 1977; Pavlou et al., 1978; Malins et al., 1980.

organic compounds other than PCBs in the water column of Puget Sound (Riley et al., 1980). The arenes identified and the mean levels observed are summarized in Table IX-3. These data were collected primarily in the industrialized embayments and hence may be biased toward high values.

TABLE IX-3

SUMMARY OF ARENE COMPOUNDS
DETECTED IN THE WATER AND SUSPENDED
PARTICULATE MATTER OF PUGET SOUND*

Compound	Concentrations	
	Dissolved, ng/l	Particulate, µg/g
Arenes		
Naphthalene	43 + 31	0.09 + 0.14
2-methylnaphthalene	14 + 7	0.02 + 0.01
1-methylnaphthalene	9 + 4	0.05 + 0.07
2,6-dimethylnaphthalene	2 + 2	0.04 + 0.04
1,3-dimethylnaphthalene	3 + 1	0.03 + 0.04
2,3-dimethylnaphthalene	1 + 2	0.01 + 0.01
2,3,6-trimethlynaphthalene	6 + 2	0.12 + 0.23
Flourene	< 4	0.03 + 0.03
Phenanthrene	10 + 8	0.23 + 0.16
Anthracene	< 1	0.10 + 0.13
Flouranthene	< 1	0.93 + 1.17
Pyrene	9 + 5	1.21 + 1.32
1-methylpyrene	< 1	< 0.9
Chrysene	< 1	< 0.03
Benzo(a)anthracene	< 1	< 0.04
Benzo(a)pyrene	No data	< 0.03
Perylene	No data	< 0.04

* Data from Riley et al., 1980. Data are averages from nine samples collected in July 1979 from Budd Inlet (1 sample), Sinclair Inlet (1), Port Madison (1), the waterways of Commencement Bay (3), and southeast Elliott Bay (3).

Concentrations of arenes in both the dissolved and particulate phases were slightly higher in the southeast Elliott Bay/Duwamish River samples and in the Blair and Hylebos waterways in Commencement Bay. However, the differences were not great and considering the large analytical uncertainty and the normal temporal variability in the water column, spatial differences cannot be established for certain.

Significant quantities of chlorinated organic compounds, including hexachlorobutadiene at levels of 0.2-3 mg/l, were observed only in the Blair and Hylebos Waterways during this study. Most of the compounds were below quantifiable levels and many could not be accurately identified. The suite of compounds was considered indicative of chlorinated industrial wastes (Riley et al., 1980). The location of these high concentrations of chlorinated industrial compounds corresponds with the distribution of similar compounds observed in the sediments (Malins et al., 1980).

Studies of the distribution of PCBs in the dissolved and particulate phases have yielded significantly more data points than obtained above. However, these studies have been limited to the Elliott Bay/Duwamish River area and other Main Basin regions (Pavlou and Dexter, 1979). These data are summarized in Table IX-4, and present a reasonably coherent picture. Away from the influence of the Duwamish River, all PCB concentrations were similar within the analytical uncertainty of the data. This uniform concentration of about 3 ng/l was observed in all non-industrialized embayments and even in the waters of the Strait of Juan de Fuca. Because of the uniform distribution, this level was interpreted as a ubiquitous "background" level which might represent the levels advected into the Sound from external sources.

TABLE IX-4

CONCENTRATION OF PCBs OBSERVED IN THE WATER AND
SUSPENDED PARTICULATE MATTER OF PUGET SOUND[a]

Region	Water, ng/l		Particulates, ng/g
	Surface (<25 m)	Deep (>25 m)	
Duwamish River	$22 \pm 13(60)$[b]		$1770 \pm 540(70)$
Elliott Bay	$7.7 \pm 7.6(64)$	$4.2 \pm 7.1(121)$	$920 \pm 200(87)$
Main Basin	4.3		$104 \pm 31(3)$
Whidbey Basin	$4.2 \pm 1.7(10)$	$5.0 \pm 3.2(5)$	$82 \pm 37(7)$
Hood Canal	$2.6 \pm 2.3(8)$	$3.7 \pm 2.2(4)$	$88 \pm 37(3)$
Northern Puget Sound and Strait of Juan de Fuca	$3.6 \pm 1.5(6)$	$4.1 \pm 2.4(3)$	

a   From Pavlou and Dexter, 1979.
b   Mean and one standard deviation. Numbers in parentheses indicate the number of samples.

Within Elliott Bay, the concentrations of PCBs in the deep water were generally near the "background" concentrations. In the surface zone (<25 m), concentrations were variable and tended to be dependent on the fraction of Duwamish River water (Dexter, 1976). Water from the latter area exhibited the highest concentrations, generally ranging from 10 to 40 ng/l total PCBs (dissolved plus particulate). While higher concentrations were often observed in the brackish surface layer of the river estuary, differences between averaged values of the surface and the more saline deep layer were not significant.

Similar studies in other embayments have not been performed. In addition, it must be noted that the results discussed above were from studies performed from 1974 through 1977. More recent data, which are not as comprehensive, indicate that current PCB concentrations in the deep waters of Elliott Bay are at the 1 ng/l level or less (R.N. Dexter, URS Company, personal communication). This apparent decrease may reflect the effectiveness of regulatory efforts to eliminate PCB inputs.

SOURCES

The identification and quantitation of the sources of trace organic contaminants has received very limited study. The levels of PCBs in effluent from Metro's sewage treatment plants and combined sewer overflow (CSOs) has been examined (Blazevich, 1973 and 1975; Dalseg, 1976; Tomlinson et al., 1976) and a recent survey in the Tacoma area identified hexachlorobutadiene in one industrial effluent (U.S. EPA, Region X, Unpublished Data, 1980). However, these discharges were generally at levels in the range of 100 ng/l or less and do not seem capable of explaining either the high levels or the spatial distribution of the trace organic residues.

For example, the PCB distribution in the sediments in Elliott Bay were consistent in part with advective transport and deposition of contaminated particulates originating in the Duwamish River and along the Seattle waterfront. Relatively high PCB concentrations have been observed in the sediments within the catch basins and effluent from CSOs and storm drains in the impacted areas (Table IX-5). However, estimates based on the average flow of these sources indicated that they could account for only a small fraction (<1 percent) of the PCBs observed in the Duwamish River sediments (Blazevich, 1973).

In addition to effluent and shore-based industrial sources, the distribution of PCB residues argues for direct inputs, i.e., spills and possibly discharges from ships via bilge pumping and over-the-side disposal. This source is indicated by the occurrence of localized patches of high PCB concentrations in the sediments some distance from shore and because these patches often consist of distinctly different assemblage of PCB isomers than observed in the surrounding sediments (Pavlou et al., 1978).

TABLE IX-5

PCB CONCENTRATIONS IN SEWAGE AND STORM DRAINS DISCHARGING
TO THE DUWAMISH RIVER

PCB Concentrations

Overflow Sites	Effluent, ng/l	Sediments,[c] μg/g wet sediment
Renton STP[d]	64[a]	
Eighth Avenue Brighton Street	520[a]	25.2
Brandon Street	110[a]	
Chelan Street		2.12
Harbor Avenue	470[a]	1.5
Hanford Street	2510[b]	19.26
Lander Street	410[a]	0.53

a - Blazevich, 1973
b - Tomlinson et al., 1976
c - Blazevich, 1975
d - For locations, see Figure IX-8

One major spill (250 gallons) of PCBs has been documented in Slip 1 of the Duwamish River (Blazevich et al., 1977; Hafferty et al., 1977). This spill, which occurred in 1974, was essentially completely dredged from the river and the contaminated sediments placed in an upland disposal site. Minimal release and transport of PCBs was observed during the monitoring of the spill and the clean-up operation. However, it can be asssumed that such incidents occurring prior to the recognition of the environmental hazards of PCBs went uncorrected and were not documented.

In comparison with the PCBs, the uses and hence possible sources of CBDs had not been established at the time this report was prepared. In large part this situation arises from the very recent identification of these compounds in the Sound. As discussed earlier, the CBDs appear to be components of a larger group of chlorinated organic compounds, all probably by-products of some industrial process. The reasoning for this conclusion is as follows.

Many additional chlorinated compounds have been identified in the water, suspended mater and sediments from the waterways of Commencement Bay (Table IX-1), but most of these were below quantifiable concentrations. In addition to the CBDs, measurable quantities of hexachlorobenzene were detected, although at very low levels in all areas except Commencement Bay. In the latter area, the hexachlorobenzene concentrations in the sediments were strongly correlated with the levels of CBDs ($r = .980$; calculated by the authors from data of Malins et al., 1980). Further, while some commercial uses of hexachlorobutadiene as an industrial solvent and as a pesticide are documented (Laseter et al., 1976; U.S. EPA, 1978), virtually no use is apparently made of other CBDs. In Puget Sound, however, the CBDs have been observed as a relatively invariant series in which the tetrachloro compounds predominated while hexachlorobutadiene was almost always less than 20 percent of the total CBDs.

These factors seem consistent with the input of the CBDs occurring as part of a mixture of chlorinated organic compounds. This origin would also be consistent with the fact that one commercial source of hexachlorobutadiene's as a by-product in the manufacture of other compounds, e.g., tri- and tetrachloroethylene, carbon tetrachloride and vinyl chloride (Li et al., 1976). Similarly, it is reasonable that a mixture of chlorinated materials would be generated in the process. The reason for the dominance of the CBDs and hexachlorobenzene may be related to the generating process or may be an artifact of the sampling and analytical methodologies. At the present time, no specific source of these compounds has been identified, although a recent survey of industrial sources in the Commencement Bay waterways did detect small quantities of hexachlorobutadiene in one industrial effluent (U.S. EPA, Region X, unpublished data, 1980).

While the data are very limited, the distribution of CBDs in the sediments appears to be similar in nature to that of the PCBs. In Commencement Bay, which undoubtedly is receiving the greatest input of CBDs, the general elevation of concentrations in the sediments may reflect that portion of the input which is transported and deposited by the advective transport from effluent sources within the Bay. In addition, however, the very high CBD levels which have been observed, apparently in patches of relatively small spatial extent and from areas which are not directly relatable to possible sources (see Figure IX-4), may reflect direct inputs from spills and/or waste dumping at the sites.

Within Elliott Bay and Sinclair Inlet, the observed concentrations of CBDs appear to be too high in some areas to represent solely advective transport from Commencement Bay. While Sinclair Inlet can receive significant inputs of waters transported from Commencement Bay via Colvos Passage, the CBD concentrations in the sediments of the Inlet exceed the levels observed in many of the Commencement Bay samples. Similarly, relatively high concentrations near Pier 54 and the Denny Way CSO in Elliott Bay indicate an impact of local sources.

As with the above compounds, specific sources of arenes have not been identified. The arenes have two origins of recognized importance. They are components, although relatively minor, of petroleum products. Similar to the PCBs, historical spills and waste disposal practices have provided many routes to the environment. In addition, recent research has indicated that many arenes are formed during the incomplete combustion of essentially all organic matter. In recent years, this source has probably resulted principally from the burning of fossil fuels; however, historically and in recent times, forest fires and related burning of wood and wood debris have provided "natural" sources of arenes. Further, this work reported the presence of arenes in soils and sediments throughout the world and observed relatively invariant ratios of major arene components in coastal areas. Both the widespread distribution and the similarities in the arene content of the samples was attributed to the commonality of combustion as the major source (Hites et al., 1980).

Some of these data are presented in Table IX-6, together with selected results from Puget Sound for comparison. The agreement in the percentages of the different compounds among these data is good for most samples, particularly regarding the dominance of arenes with greater than 3 rings. This multi-ring dominance is considered characteristic of the formation of the compounds from combustion.

Petroleum, in comparison, is generally characterized by a dominance of multialkylated arenes of less than 4 rings (Blumer, 1976; Griest, 1980). A few samples from the Sound, e.g., from the Puyallup disposal site showed relatively more arenes of 4 rings or less (Table IX-6). These samples may indicate some petroleum contamination, but they appear to be of limited importance.

While on a global basis atmospheric inputs may be significant (Hites et al., 1980), within the Sound the very high heterogeneity and the strong gradients in the sediments argue against this source as a major direct input. At the same time, a recent survey in the Duwamish River basin indicated that arenes, originating from automobile exhaust, constitute a significant fraction (>50 percent) of the organic matter associated with the air-borne particulates (Olsen et al., 1975). Thus, it is possible that both direct and indirect (e.g., street runoff) atmospheric pathways may provide at least a portion of the arene load from urban sources.

FATE OF ORGANIC COMPOUNDS

In comparison with the trace metals, studies of the transport of organic contaminants are limited both in terms of studies specific to Puget Sound and in supporting information in the literature. The exception to this is studies of PCBs and the chemically similar organo-chlorine pesticides for which a considerable body of data exists. As a

TABLE IX-6

COMPARISONS OF THE RELATIVE CONCENTRATIONS OF SELECTED
ARENES FROM EAST COAST SEDIMENTS AND SOILS WITH THOSE
ARENES FROM PUGET SOUND SEDIMENTS

Sample	Arene Concentrations, ng/g (%)[a]				
	Phenanthrene[b]	Flouranthene[b]	Pyrene[b]	C_{18}^c	C_{20}^d
East Coast[e]					
Charles River (Boston)	5000 (5.8)	15000 (17)	13000 (15)	21000 (24)	33000 (39)
Maine Soil	70 (10)	120 (18)	100 (15)	140 (21)	250 (37)
Gulf of Maine	43 (8)	120 (22)	100 (18)	80 (15)	200 (37)
Buzzards Bay 1	53 (7)	130 (16)	120 (15)	160 (20)	340 (43)
Buzzards Bay 2	42 (5)	130 (15)	120 (14)	200 (23)	380 (44)
Buzzards Bay 3	8 (13)	11 (17)	7 (11)	12 (19)	25 (41)
New York Bight	740 (13)	1200 (21)	1300 (22)	890 (15)	1700 (29)
Puget Sound[f]					
Pier 54 (Elliott Bay)	6800 (13)	7600 (15)	11000 (22)	12800 (25)	12600 (25)
West Waterway (Duwamish River)	2600 (10)	3700 (14)	3200 (12)	5100 (19)	12130 (45)
Elliott Bay, Mid Bay	320 (10)	450 (15)	540 (18)	550 (18)	1200 (39)
West Point, Northside	4200 (10)	6100 (15)	8500 (20)	8700 (20)	15000 (35)
Hylebos Turning Basin	400 (3)	1700 (14)	1600 (13)	4000 (32)	4800 (38)
Puyallup Disposal Site	50 (36)	30 (22)	20 (15)	20 (15)	17 (12)
Brown's Point	90 (18)	90 (18)	100 (20)	80 (16)	130 (27)
Old Tacoma	1900 (15)	2600 (20)	2100 (16)	3800 (30)	2370 (19)
Pt. Herron (Sinclair Inlet)	1400 (10)	2300 (16)	3100 (21)	3600 (25)	4070 (28)
Port Madison (Mid)	60 (11)	80 (14)	110 (20)	120 (21)	190 (34)
Reach Island (Case Inlet)	50 (10)	100 (20)	90 (18)	80 (16)	180 (36)
Budd Inlet (South end)	70 (8)	160 (17)	170 (19)	200 (22)	310 (34)

a Percentages (numbers in parentheses) of the compounds/classes of compounds were calculated from the sums of the listed compounds.

b Values are for single compounds.

c For East Coast samples includes chrysene, triphenylene and other $C_{13}H_{14}$ isomers; for Puget Sound samples include chrysene and benzo(a)anthracene.

d For East Coast and Puget Sound samples includes benzofluoranthenes, benzopyrenes and perylene.

e Laflamme and Hites, 1978.

f Malins et al., 1980.

result, this section will rely heavily on the latter studies with comparison among the groups of compounds used to expand the applicability of the available data. Additional information for specific priority pollutants has recently been reviewed (Callahan et al., 1979). These data appear to fit the generalized scenario presented below.

Two major processes have been identified which control the distribution of the compounds in question: 1) exchange of the compounds among the abiotic components of the system, water (dissolved), suspended particulate matter, and sediments; and 2) degradation of the compounds (Pavlou et al., 1976). The first process provides the link between the inputs and movement of the residues within the physical system. As with the trace metals, of primary concern is the relative fractionation of compounds between the advective components and the less mobile ones.

Degradation, either abiotic or in association with microbial or metabolic processes, results in the destruction of the parent organic compound. This process is distinct from the change in speciation which results from chemical reactions of trace metals. The metals are essentially indestructable and may cycle repeatedly through a number of different chemical forms within the environment. Chemical reactions of the organics, however, result in the formation of new compounds, generally within a series of reactions leading ultimately to either the complete destruction of the compound (metabolized to CO_2 and H_2O) or to the incorporation of molecular fragments into refractory organic polymers, e.g., humic acids. As noted below, however, degradation of the contaminants of concern in this study may be very slow and, in addition, may lead to the formation of compounds more toxic than the parent.

Exchange between Water and Suspended Particulate Matter

Based on the accumulated evidence, recent studies have presented a reasonably coherent model for the exchange of PCBs between the dissolved and particulate phases (Dexter, 1976; Dexter and Pavlou, 1978a; Pavlou and Dexter, 1979). These studies are summarized below.

Theoretical considerations, together with field and laboratory verification, indicate that the distribution of PCBs at the levels encountered in Puget Sound is controlled by equilibrium partitioning. Under this model, the PCBs are absorbed to the particulates at a concentration which is linearly dependent on the dissolved concentration, such that the relationship can be defined by a constant, K, the distribution ratio, equivalent to a partition coefficient:

$$C_{i,p} = K_i \, C_{i,w}$$

where $C_{i,p}$ and $C_{i,w}$ are the concentrations of compound i in the particulate and dissolved phases, respectively.

According to the model, K_i is a function of physical and chemical characteristics of the water and particulates. Within Puget Sound, the major factors which were identified were the salinity (ionic strength) of the water and the size and organic content of the particulates. Increasing salinity should decrease the solubility and increase the adsorption through the "salting-out" effect. Smaller particles have a higher surface area-to-mass ratio so that the concentration on a mass basis increases with decreasing particle size. Thermodynamic calculations and laboratory studies indicate that the natural organic matter should be a preferred sorption material.

Actual measurements of the concentrations of PCB in the water and on the particulates in the Sound, principally within Elliott Bay/Duwamish River, tend to support this model (Figure IX-9). However, neither the particle size nor the total organic content were measured for these particulates, while the salinity range of samples was limited. As a result, the dependence on salinity, particle size and/or the fraction of organic matter could not be established (Dexter and Pavlou, 1978a). However, Hom (1978) in a recent study of PCBs in the sediments, did observe a correlation between PCBs and the total organic content within individual cores from Elliott Bay and the Duwamish River. No relation to specific surface area of the particles was observed. In addition, attempts to correlate the PCB concentrations with any sediment parameter among different sampling sites failed due to the high spatial variability.

Similarly, comparisons of the concentrations of PCBs and arenes in the sediments from Port Madison and Case Inlet (Figure IX-10), areas which would be expected to receive a major portion of the input from advective transport (see below), indicate that sediment size and/or the fraction of total organic matter are important controlling parameters in the accumulation of non-polar organic compounds. As in the previous study, however, spatial heterogeneity, apparently induced by localized inputs, obscured the trends in the relationships of the concentrations of PCBs, CBDs or arenes and either sediment particle size or fraction of organic matter when comparisons were made among data from different embayments (Figure IX-11).

Besides the chemical and physical parameters of the system, molecular characteristics of the organic contaminants also have a major effect on the exchange process. As a general rule, two types of inter-molecular interactions can be considered in describing the interaction between the organic contaminants and the components of the environment: electrostatic and hydrophobic interactions. Increased polarity of the organic contaminants results in stronger attraction to the polar components of the system. In natural aquatic systems, increased polarity generally
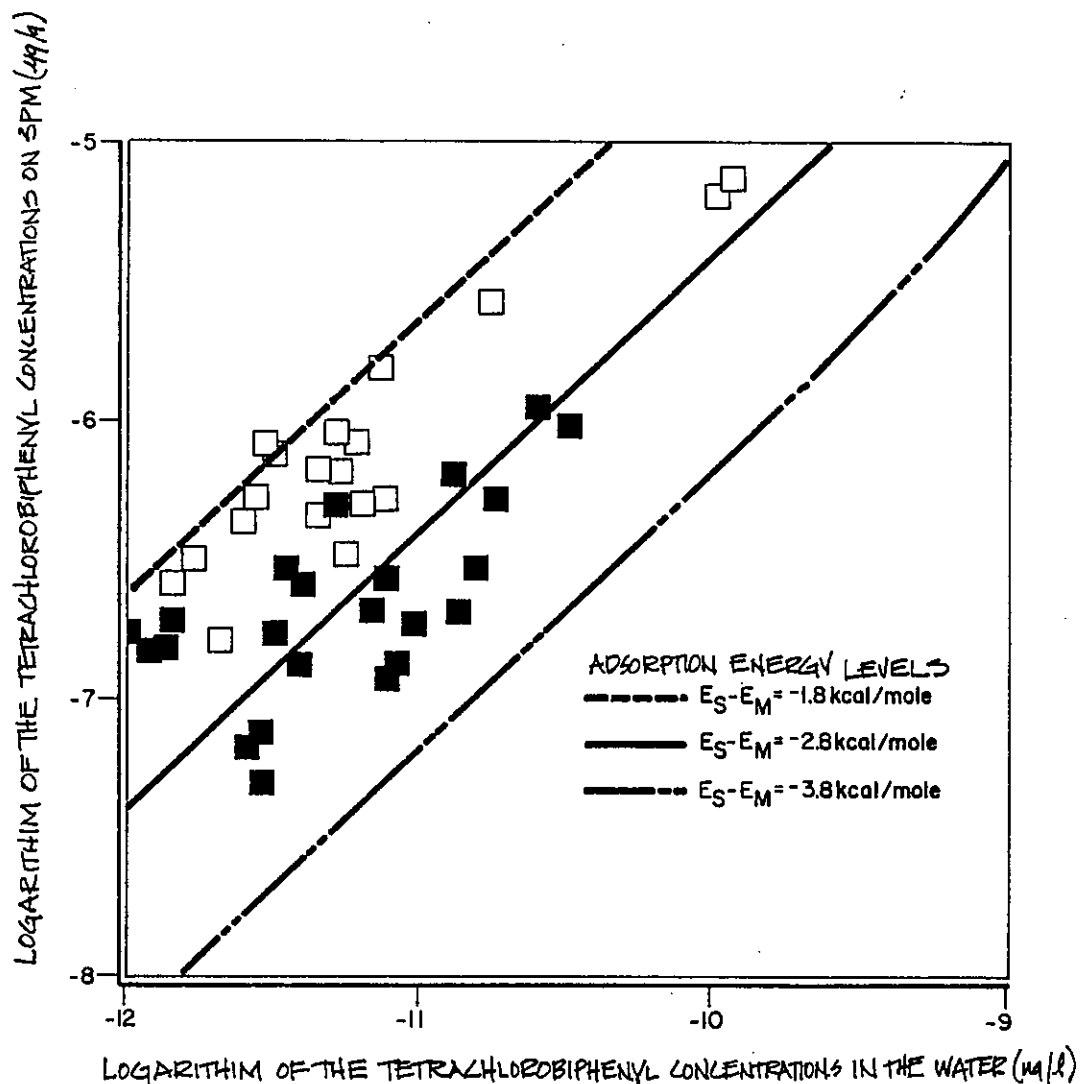
Figure IX-9. Plots of Logarithms of the Concentrations of Tetrachloro-
biphenyls Observed on the Suspended Particulate Matter as a Function of
the Water Concentration in Elliott Bay (■) and the Duwamish River (□).
Lines show the theoretically predicted relationship at three adsorption
energy levels.

From Dexter and Pavlou, 1978a
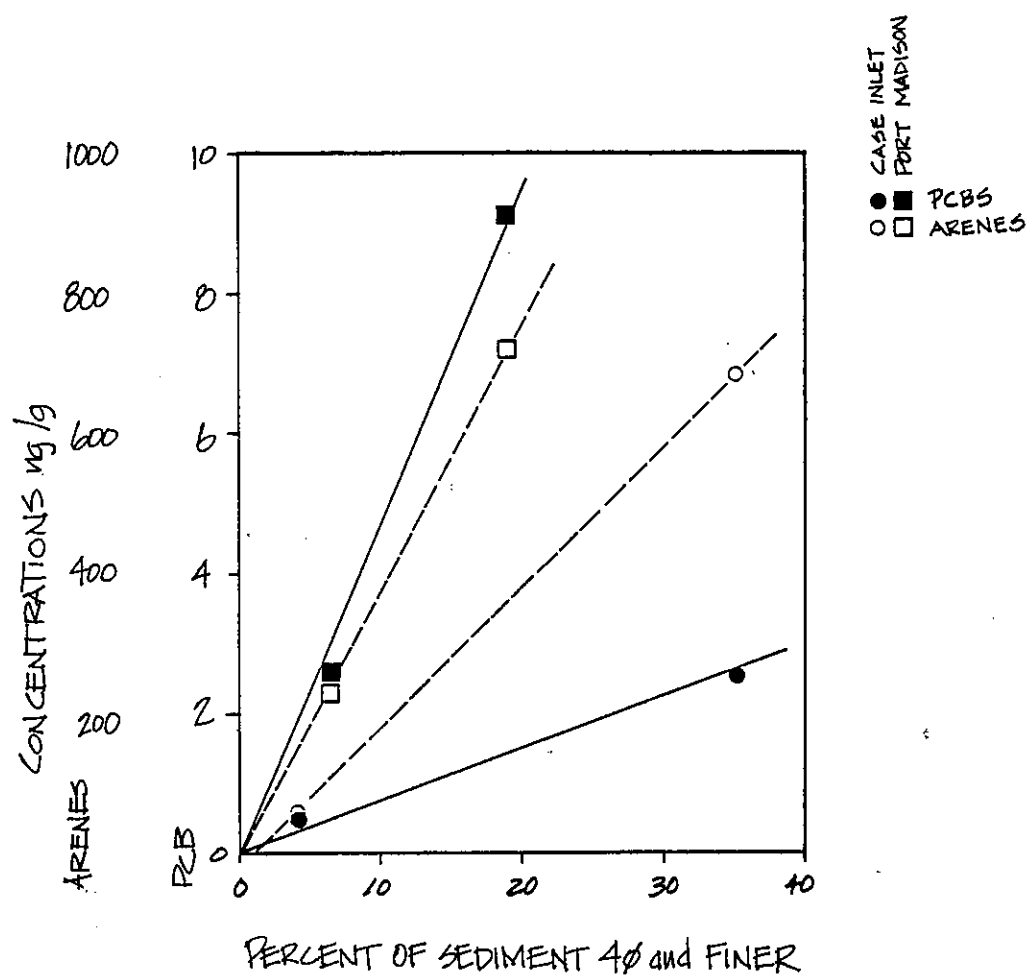
Figure IX-10. Plots of the Concentrations of PCBs and Arenes Observed in the Sediments of Case Inlet and Port Madison Versus the Grain-Size of the Sediments. Lines were subjectively drawn to illustrate trends in the data.

Data from Malins et al., 1980.
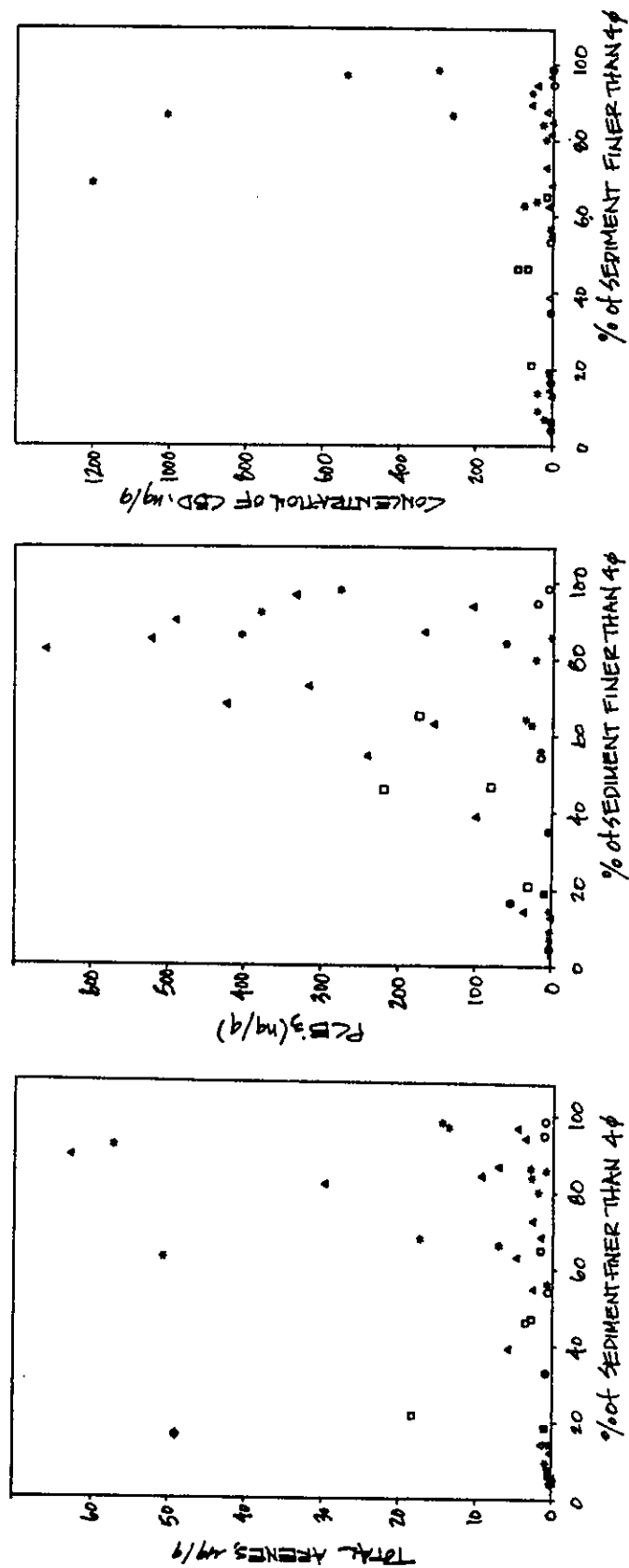
Figure IX-11. Scattergrams of the Concentrations of PCBs, CBDs, and Arenes Observed in the Sediments Versus (a) the Grain-Size of the Sediments.

Data from Malins et al., 1980.
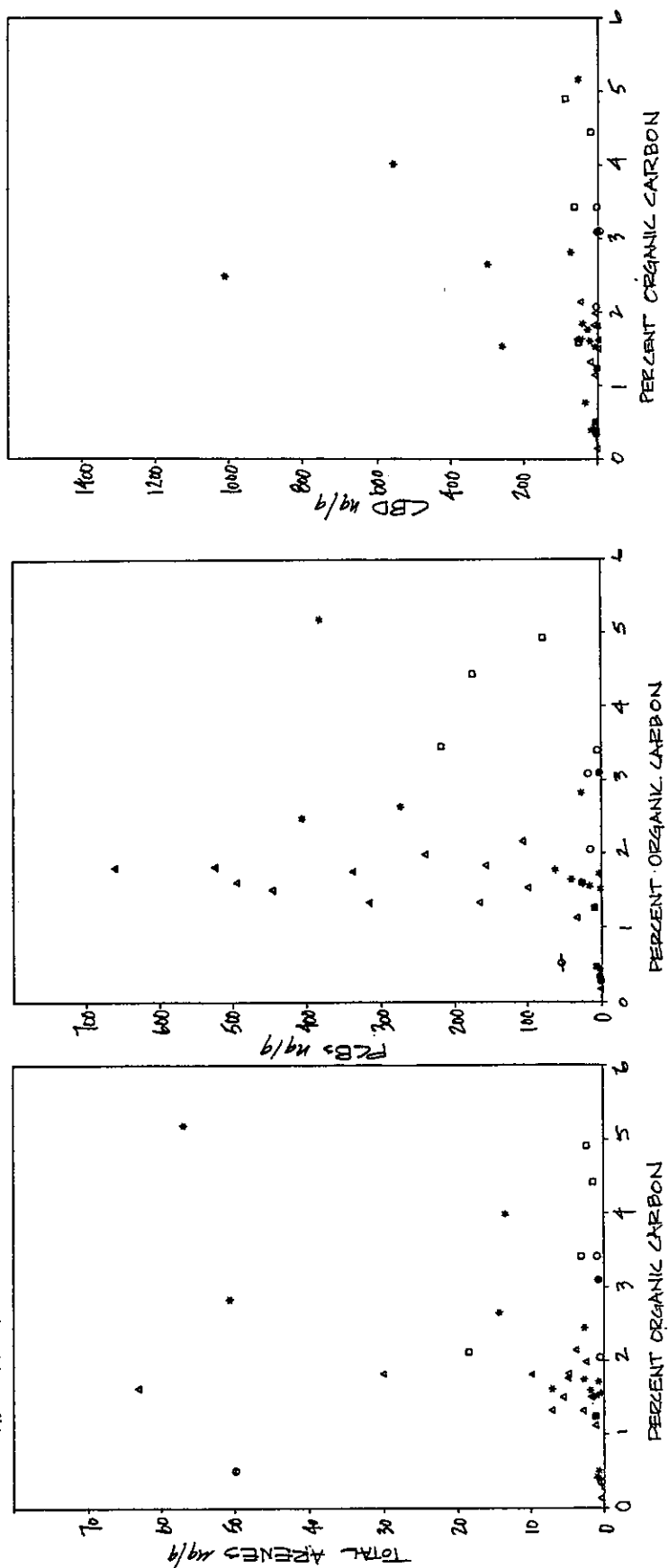
Figure IX-11 (Continued). (b) Versus the Percent Organic Carbon of the Sediments.

Data from Malins et al., 1980.

results in a greater affinity for the dissolved phase and lower sorption on particulate phases compared to less polar molecules.

Hydrophobic interaction results from the solvent characteristics of liquid water (Ben-Naim, 1974; Franks, 1975). Due to the strong hydrogen bonding among water molecules, considerable structure, i.e., specific molecular arrangements, is present in water even in the liquid state. Introduction of a solute disrupts the normal structure and requires the rearrangement of the water molecules in the vicinity of the solute molecule. This restructuring requires energy and thus acts as a repulsive force limiting the accommodation/solution of the molecules. The electrostatic attraction of the water molecules to ionic and strongly polar solutes compensates for the hydrophobic interaction and such substances are readily soluble. Many organic compounds, and particularly those of immediate consideration in this report, are of low polarity and hence are sparingly soluble.

In addition, in a somewhat simplified model, the amount of restructuring and hence the strength of the hydrophobic interaction increases with the size of the organic molecule. Thus homologous series of low polarity organic compounds show decreasing solubility with increasing numbers of carbon atoms in the molecules (McAuliff, 1966). Between compounds of widely different molecular constituency, sorption results from the balance of polar attraction and hydrophobic interaction; but, since the solubility also reflects a similar balance of forces, sorption generally is an inverse function of the solubility (Chiou et al., 1979).

The data from Puget Sound demonstates this dependence on molecular structure. Figure IX-12 compares the concentrations of PCBs of varying degrees of chlorination and selected arenes observed in the water, suspended particulate matter, and sediments from stations in Puget Sound. Both the PCBs and arenes showed relative enrichment in the water phase of the smaller, more soluble compounds and selective sorption of the less soluble ones. For PCBs, the data have been sufficient to quantify this relationship in terms of the concentration ratio, K, which was observed to increase regularly from approximately 4.4×10^4 for trichlorobiphenyls to 9.7×10^4 for heptachlorobiphenyls (Pavlou and Dexter, 1979). (K was expressed as the ratio of the g PCB/g dry suspended matter to the g PCB/g water.) The data for the arenes, while qualitatively comparable, are too limited to provide accurate estimates of K, or to firmly establish that partitioning is equally applicable. However, for comparison, K values for selected arenes with established solubilities were calculated from the averaged data in Table IX-3, and an average K for hexachlorobutadiene was calculated from the data obtained in the Hylebos and Blair Waterways (Riley et al., 1980). These data are plotted in Figure IX-13 as a function of solubilities of the compounds. Considering the imprecision of data, the agreement with the PCB values is good.
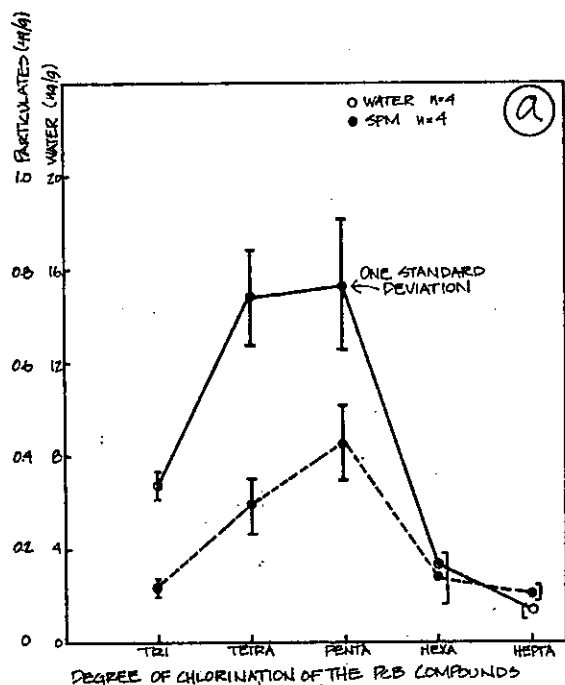
-367-
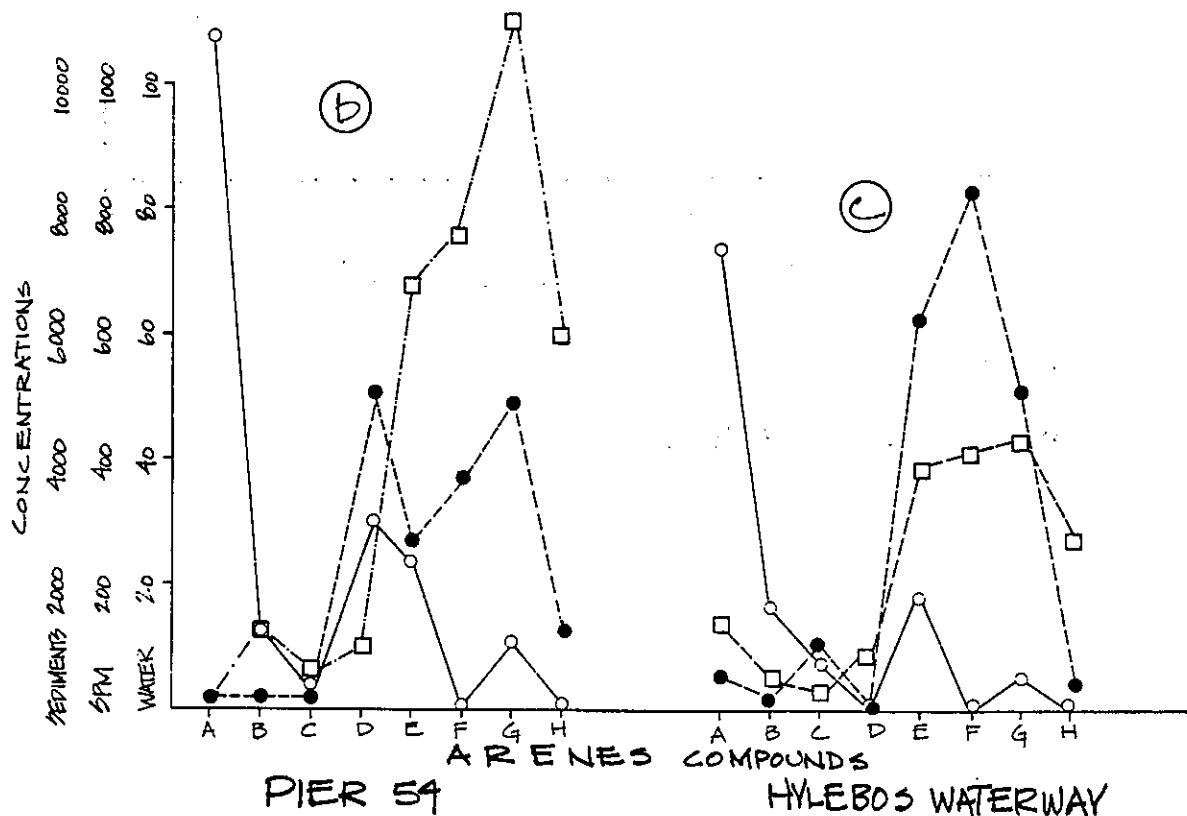
Figure IX-12. Plots of the Concentrations of PCBs and Arenes Observed in the Water, Suspended Particulate Matter and Sediments from Selected Sites in Puget Sound: a) PCBs in the Duwamish River (Dexter, 1976); b) Arenes near Pier 54 (Riley et al., 1980; Malins et al., 1980); and c) Arenes in the Hylebos Waterway (Riley et al., 1980; Malins et al., 1980).
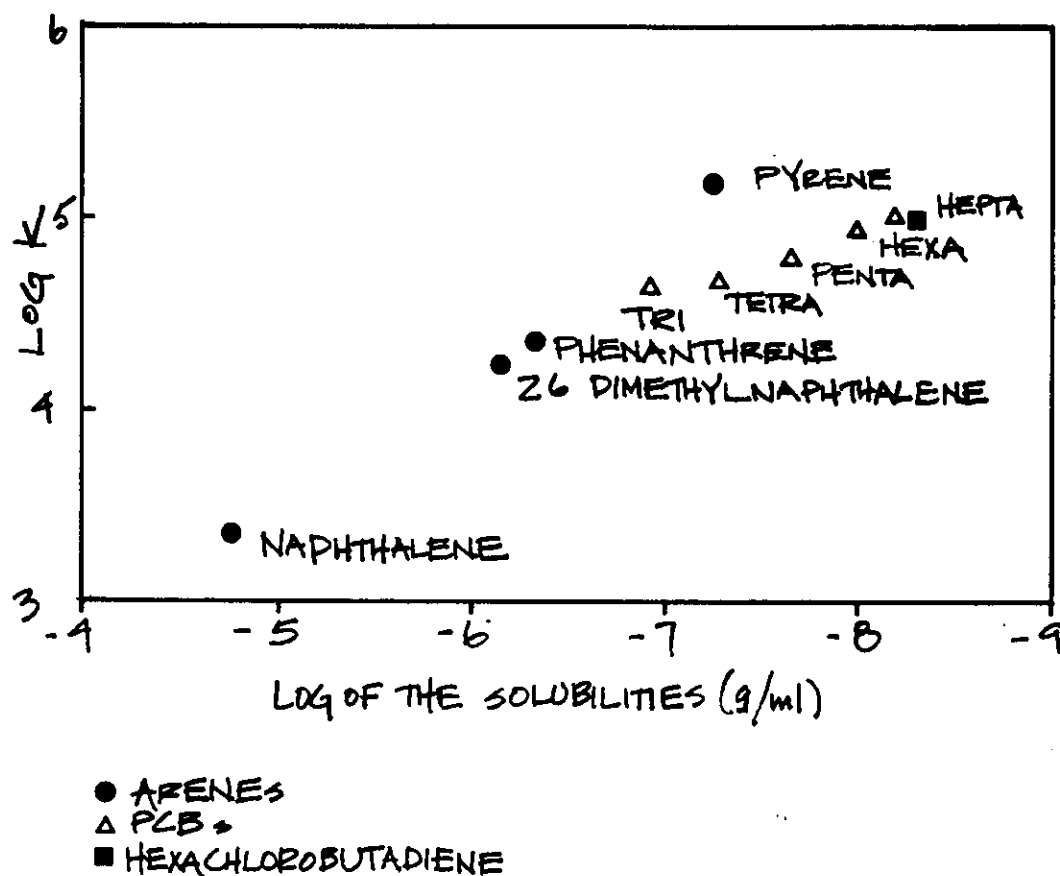
Figure IX-13. Plots of the Logarithms of the K Values for PCBs, Hexachloro-
butadiene, and Selected Arenes Observed in Puget Sound. K Values for
PCBs from Pavlou and Dexter, 1979; for Arenes and Hexachlorobutadiene
calculated from the data of Riley et al., 1980. Solubility Data for
PCBs from Dexter and Pavlou, 1978b; arenes from May, 1980; and hexachloro-
butadiene from U.S. EPA, 1978.

An important point which must be recognized in considering these compounds is that even though much higher concentrations of the organic pollutants may be associated with the particulate matter compared to the concentrations in the water, in most areas of the Sound the total suspended load is very low (1 to 2 mg suspended particulate matter/l). As a result, even for strongly accumulating compounds, the greatest fraction of the contaminant will be in the dissolved phase. This point is illustrated in Figure IX-14 which shows calculated plots of the fraction of particulate-sorbed compounds as a function of the concentrations of suspended matter. Plots for a number of distribution ratios (K) are shown, together with field and laboratory data for PCBs on suspended matter from Puget Sound. Even though the particulate concentrations of PCBs are roughly four orders of magnitude greater than the corresponding concentrations in the water, generally less than 10 percent of the PCB residues in a volume of seawater were associated with the particulates.

The net effect of this distribution is two-fold. First, away from areas with high particulate concentrations, the transport and distribution from a source is controlled primarily by advection. The levels in both the water and suspended matter will reflect essentially conservative mixing of the source and background water. This has been observed in a series of surface water samples taken on a transect from the Duwamish River to the Main Basin through Elliott Bay (Pavlou and Dexter, 1979). In this series of samples, the PCB concentrations (dissolved plus particulate) decreased conservatively with increasing salinity. The behavior of two PCB components, the tri- and pentachlorobiphenyls, are shown in Figure IX-15. Considering the rapid transport and complete mixing of the water within Puget Sound, then, it is not surprising that PCBs, CBDs and arenes have been observed in all areas examined.

Secondly, applying the same principles to the residues which have accumulated in the sediments indicates that, due to the very high particulate to water ratio, equilibration with the interstitial water requires only a negligible fraction of the sediment-sorbed residues. As a result, while the residues appear to be easily released, as determined by laboratory elutriate tests (Dexter, 1976) and will reequilibrate upon resuspension, diffusion and relocation within the undisturbed sediments is slow. This is demonstrated by the depth profiles of PCB concentrations in the sediments (Figure IX-7) which showed very high PCB gradients, and by the continued presence of localized areas of high PCB concentrations (Figure IX-6).

DEGRADATION

No specific studies of the degradation of the trace organic contaminants have been performed in Puget Sound. While there is probably no compound totally resistant to abiotic and biologically mediated reactions,
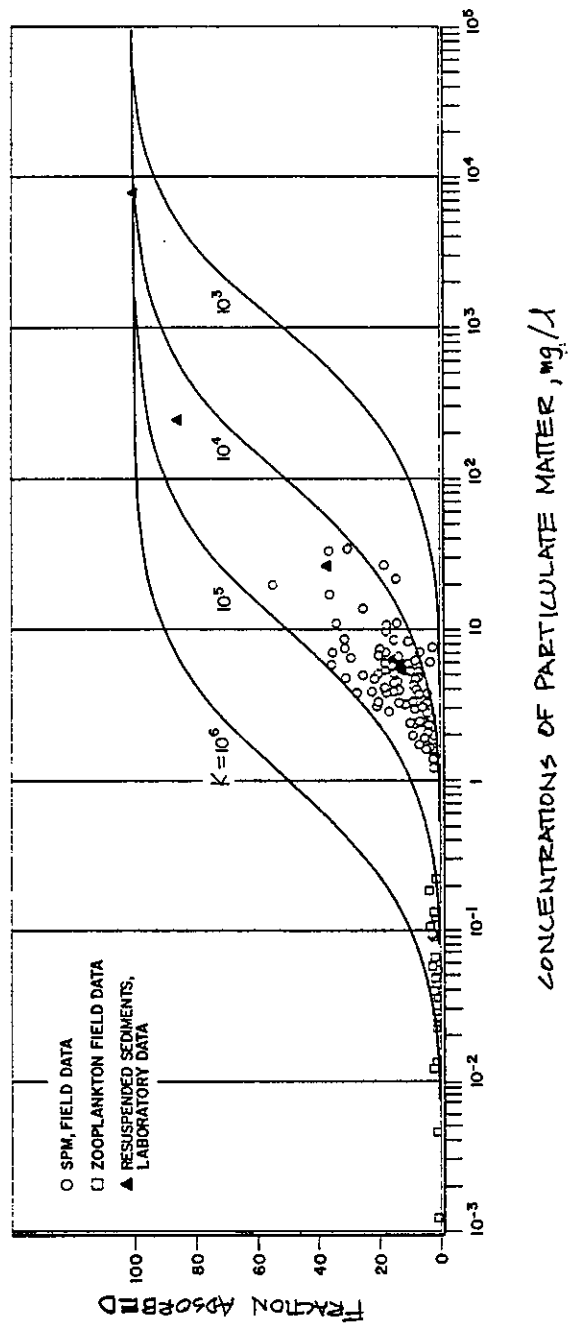
Figure IX-14. Plots of Percent of Organic Contaminants Associated with the Suspended Particulate Matter as a Function of the Suspended Load. The solid lines represent the theoretical predictions for a number of K values. Symbols present values for PCBs for SPM and zooplankton observed in Puget Sound and in laboratory desorption experiments.

From Pavlou and Dexter, 1979.
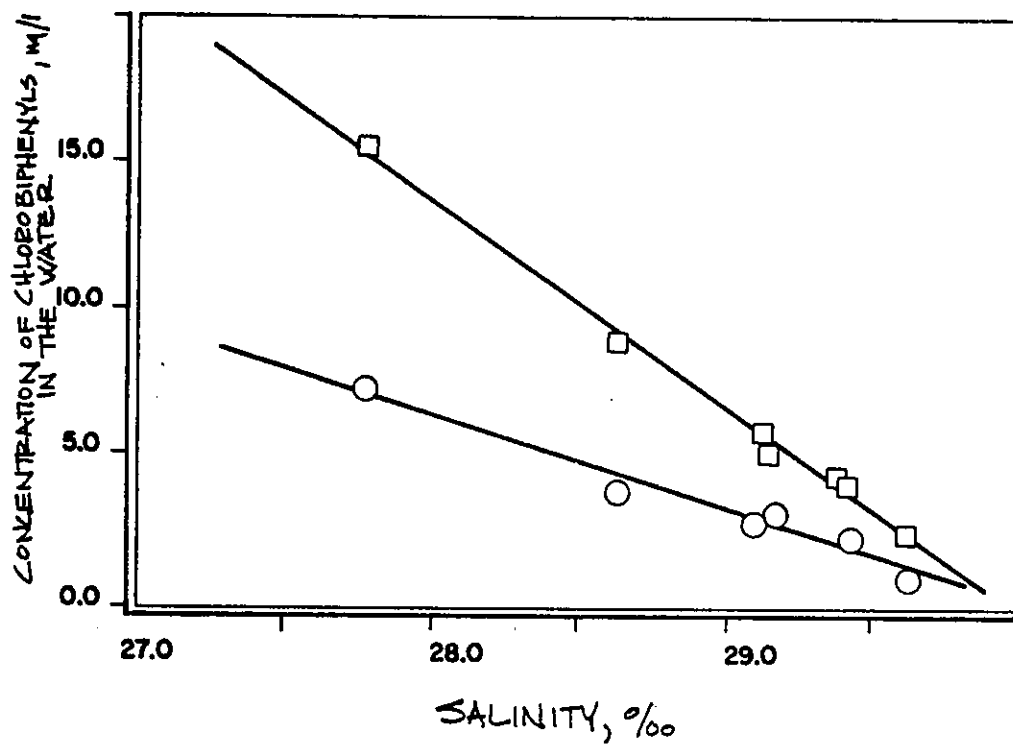
Figure IX-15. Plots of the Concentrations of Tri- (O) and Pentachlorobiphenyls
(□) in the Water as a Function of Salinity for the Duwamish River and
Elliott Bay.

From Pavlou and Dexter, 1979.

field data from most areas and from the Sound tend to indicate that many of the compounds discussed herein are long-lived in natural systems.

Abiotic reactions, e.g., hydrolysis and photolysis, are generally high energy reactions requiring heat or light (Larson et al., 1976). For the compounds of interest, these processes are most likely not of great importance in the aqueous environment of Puget Sound. Metabolic degradation routes have been identified for arenes (Philpot et al., 1976; Gibson, 1976; Willis et al., 1980) and PCBs (Safe et al., 1980; Furukawa and Matsumura, 1976). However, these reactions tend to be limited to the more complex enzymatic systems of higher animals. In particular, bacteria, which should have a great ability to degrade most organic matter, have limited capacity to degrade the more complex arenes and more highly chlorinated PCBs (Gibson, 1976; Furukawa and Matsumura, 1976).

Concentration gradients of PCBs in cores from Puget Sound in general correspond to the probable long-term historical input rates, i.e., increasing levels in more recent sediment (Hom, 1978; Dexter et al., 1979). The same profiles would tend to be produced by more complete degradation with time of burial, but the residues in the cores do not indicate the preferential reduction in the relative concentrations of the less chlorinated components which should be induced by metabolism. (Note that any very recent decreases in PCB inputs, as indicated by decreased concentrations in the water column, have not been detected in the sediments, which may simply reflect the difficulty in sampling the very surface sediments.)

The concentrations of arenes showed similar general decreases to low levels at depths in the sediments corresponding to pre-1900 in dated cores (Carpenter and Fairhall, 1979). However, many of the components showed a strong subsurface maximum which was not readily explainable from input considerations. In addition, the relative concentrations of the various arenes also varied with depth. As a result, it cannot be clearly established that the levels of arenes are not significantly altered by metabolism.

At the present time, no data are available regarding the trends in the concentrations of other chlorinated organics, e.g., the CBDs. Literature information on the metabolism of these CBDs was not found. It may be worth noting, however, that while tetrachlorobutadienes most often dominated the CBDs in the sediments, hexachlorobutadiene generally dominated in the biota. The latter component was often the only detected CBD (Malins et al., 1980). These data may indicate selective metabolism of the less chlorinated CBDs.

TRANSPORT

The foregoing discussions can be used to establish the general
transport scenario presented schematically in Figure IX-16. This
scenario has been developed primarily from the data on PCBs in Elliott
Bay/Duwamish River. The major points are discussed below.

While few specific input sources have been identified, two types of
inputs were indicated. One source apparently has been located in the
Duwamish River estuary which has led to the contamination of the
water and suspended particulates in both the surface brackish layer and
the deeper saline layer. Sedimentation within the estuary has resulted
in the fairly uniform contamination of broad reaches of the river
sediments.

As the contaminated water and particulates exit the river estuary,
the dominant flow carries the material along the eastern side of Elliott
Bay where it is possible that additional inputs occur, e.g., from CSOs.
During this advective transport, several events occur. Mixing with less
contaminated water results in the dilution of the residues. Reduction
of the dissolved concentration should induce release of residues from
the more contaminated particulates, while relatively uncontaminated
particulate matter from the "clean" water absorbs additional residues.
The final concentration on the particulates should reflect the new
concentration in equilibrium with the diluted water. During the transport,
particulates settle from the water column leading to the widespread
contamination of the sediments of Elliott Bay in a pattern reflecting
the dilution pattern in this overlying water.

However, in the natural system, it is not completely clear whether
desorptive equilibrium does in fact occur. The concentrations of PCBs
in surface sediments (upper 2-3 cm) associated with the "hot spots" of
very high levels of PCBs are certainly not in equilibrium with the
overlying water. Still, these residues appear to be stable for long
periods. This stability may reflect the fact that sampling collects a
much deeper layer than what may actually be involved in exchange with
the overlying water, or may indicate permanent binding to the sediment
particles.

Further, the general trends in the PCB concentrations in the
sediments of Elliott Bay follow the transport pattern of the surface
waters. Measurements made in the deep water (>25 m) of the Bay indicated
this zone is basically at background PCB levels (see Distribution in
Water Column section). Thus the deposition pattern in the sediments
appears to require particulate transport from the more contaminated
surface through a deep layer of relatively lower concentrations prior to
deposition. Either the particulates do not desorb significantly or else
another transport mechanism is involved.
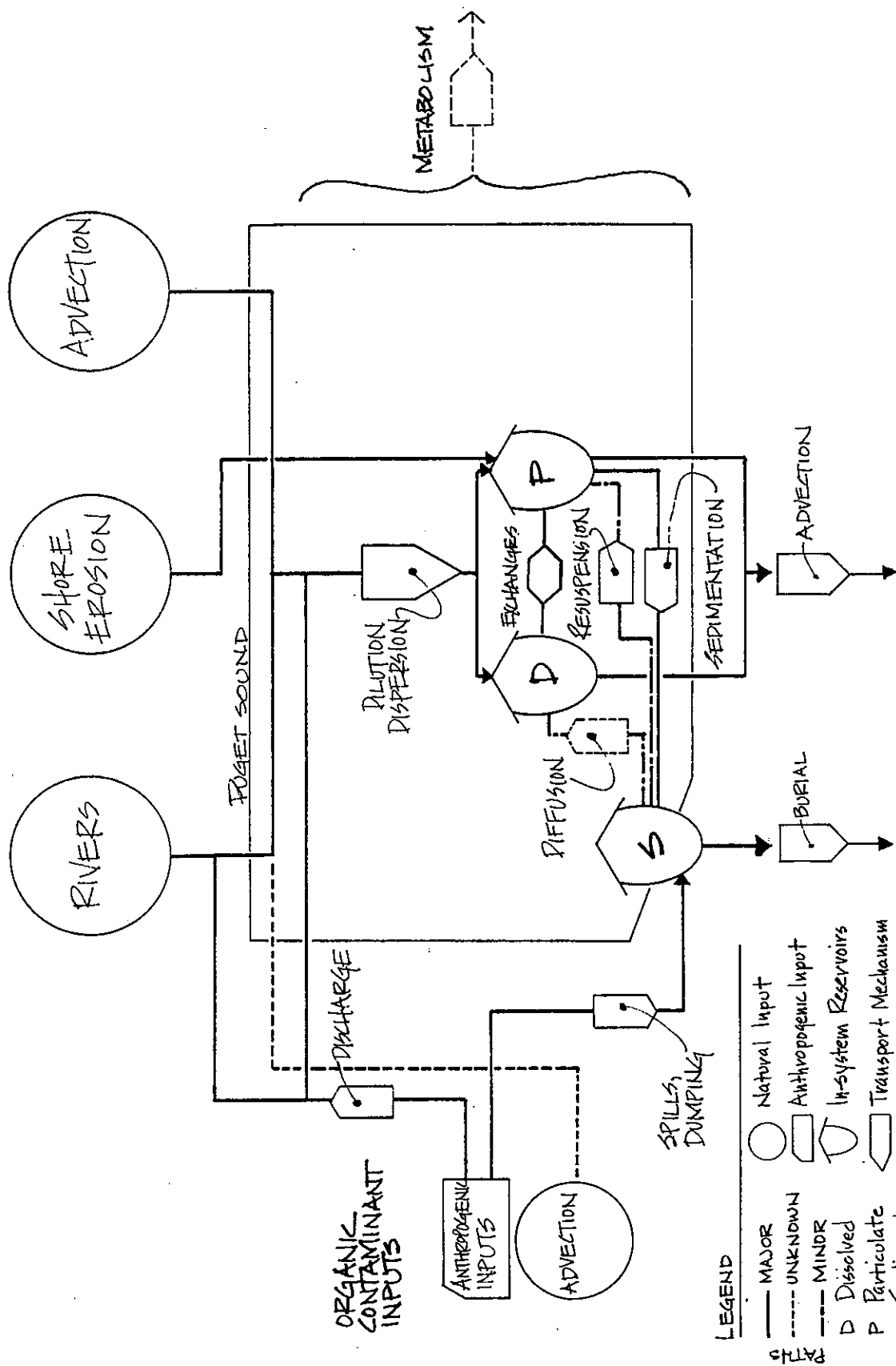
Figure IX-16. Diagram of the Major Transport Processes for Organic Contaminants.

By the time the river water exits the bay, it has mixed to the extent that the residue levels are not sufficiently above the background levels in the Sound to be distinguishable. PCB concentrations in the water, particulates and sediments of the northern Main Basin, Whidbey Basin and Hood Canal were very similar (Pavlou and Dexter, 1979; Hom, 1978), demonstrating the dominance of mixing and advective transport away from strong input zones. Since these areas also receive significant sediment inputs from local rivers and from shoreline erosion, the similar PCB levels in the sediments indicate the importance of sorption from the water column into the settling particulates. The mass flux of PCBs to the sediments, however, involves only a small fraction of the total available in the water column.

Within the urbanized embayments, localized areas of high concentrations of different PCB residues in the sediments probably reflect spills and/or dumping of waste materials, including contaminated dredged material. These inputs do not appear to enter into the advective flow to a measurable extent but rather are an addition to the levels generated by the mean transport of water and particulates.

As discussed previously, once the residues have accumulated in the sediments they appear to be chemically and biologically stable. High and variable gradients even in deeper deposits indicate that desorption and diffusion within the sediments are very limited.

Although the data are much more limited, similar scenarios appear to apply to the other urbanized inlets and bays, each of which has its own sources of PCBs. In all cases, the data indicate the presence of PCB concentration gradients reflecting the dominant circulation pattern. Levels decrease away from areas in proximity to the input sites, e.g., harbors. At least in Commencement Bay, "hot spots" of non-advectively transported residues are also present, similar to those observed in Elliott Bay.

The lower concentrations of PCBs observed in Budd Inlet and the Southern Sound compared to those observed in most of the areas north of The Narrows is somewhat difficult to explain on the basis of the advective transport model discussed above. Water entering the Southern Basin from the Main Basin should contain the same PCB levels as observed in the northern regions. However, it has been noted (Chapter II) that local fresh water inputs are sufficient to significantly dilute the incoming water. The freshwater inputs may also dilute the residues.

Based principally on the limited measurements made in sediment samples, the same scenarios appear applicable to the industrial chlorinated hydrocarbons (e.g., CBDs) and the arenes. For the former, however, one or a few sources in Commencement Bay appear to currently dominate

the system and transport to other areas of the Sound may originate primarily from this area. Due to the complete mixing and rapid movement of water in The Narrows, residues originating in Commencement Bay should be rapidly incorporated in the mean advective transport of the Sound.

The trends in the distributions of arenes in the sediments and water columns appear to follow those of PCBs quite closely. However, the data are so limited at the present time that major features of the model, such as the advectively generated gradients in the sediment concentrations seen for PCBs, are not adequately established to ensure its complete applicability. The data do indicate that the multi-ring arenes exhibit as strong or stronger binding to the sediments as observed for the PCBs.

TEMPORAL TRENDS

Data are sufficient only for PCBs to make any estimates of the temporal trends in the levels of organic contaminants. The general trends in cores taken from Elliott Bay reflect the historical increase in the use of PCBs, which began about 1930. In the late 1960s and 1970s, environmental concern led to reduced domestic production and eventually to regulatory efforts to completely eliminate usage of these compounds. The sediment concentration profiles depict the increase in PCBs, but as yet do not appear to be showing any decreases in recent sediments. However, as noted above, the PCB levels in the water column in Elliott Bay appear to have decreased significantly over the last 5 years from concentrations of 3 to 5 ng/l in 1975 to recent levels of 0.5 to 1 ng/l.

The apparent lack of decrease in the sediments may result from the difficulty in sampling very recent sediments or may result from continued resuspension of previously contaminated material from the river estuaries. If the trend in the water column is a real reflection of decreasing inputs, the physical stability of most sediments in the Sound and the limited movement of the PCBs within sediments indicate that eventual burial and isolation from the system are likely. It should be noted, however, that the chemical stability of the PCBs is great and thus the residues will probably be present in the sediments for some time. Similarly, it can be reasonably assumed that major inputs of the industrial chlorinated hydrocarbons and anthropogenic arenes have been a recent phenomena, i.e., within the last 50 to 80 years. Recent trends are unknown.

CONCENTRATION IN BIOTA

Spatial Distributions

The concentrations of organic trace contaminants have been examined in a variety of organisms in Puget Sound. Most of these data, however, have documented the levels of PCBs and chlorinated pesticides with only one recent study of other compounds. In addition, the available data are difficult to integrate for many of the same problems discussed relative to the levels in sediments. These are:

1. To provide wide scale spatial comparisons, studies covering a multi-year period and representing samples from different seasons must be compared. The limited available data do not allow for the evaluation of the importance of any temporal effects.

2. The data available are based on a variety of sampling, sample preparation and data reporting methods. For example, concentrations of PCBs in fish have been reported for whole-body burdens, levels in muscle tissue, and levels in liver; and on a wet weight, dry weight and lipid weight basis. Variability in these factors among the organisms largely prevents intercomparisons of the residues when different tissues and/or normalization factors are used.

3. While the levels of contaminants have been examined in a number of organisms, few synoptic studies of the same species have been made. As above, physiological differences limit meaningful comparisons between species.

Fortunately, the trends in the spatial distributions of the organic residues in the biota have been observed to be similar among species and in general reflected the same trends as observed in the sediments. Data for two groups of organisms which have received significant spatial characterization of body burdens are presented in Tables IX-7 and IX-8.

Table IX-7 presents data for zooplankton (primarily copepods, euphasiids and ctenophores) and shrimp. Only PCBs were measured in the zooplankton samples. Spatial trends in the PCB concentrations showed a general correspondence with levels observed in the sediments, e.g., levels in shrimp were highest in the Hylebos Waterway and in the Duwamish River. Away from these areas, levels were similar except for lower levels observed in the Strait of Juan de Fuca. These spatial differences were not as great as those observed in the sediments and may reflect primarily physiological differences, particularly in the amounts of lipid, among the species dominating each site (see following discussion).

TABLE IX-7

MEAN CONCENTRATIONS OF PCBs, CBDs, HEXACHLOROBENZENE (HCB)
AND 3-TO 5-RING ARENES IN ZOOPLANKTON AND BENTHIC SHRIMP
FROM REGIONS OF PUGET SOUND.

| Sampling Location | Concentrations, ng/g dry weight | | | |
	PCB	CBD	HCB	3-5 Ring Arenes
Strait of Juan de Fuca (1)a,b	70	-[e]	-	-
Whidbey Basin (12)[b]	955+701[d]	-	-	-
Hood Canal (4)[b]	118+87	-	-	-
Main Basin (8)[b]	825+769	-	-	-
Port Madison (1)[c]	304	10	1	120
Sinclair Inlet (1)[c]	680	NQ[f]	0.4	950
Elliott Bay (9)[b,c]	961+380	NQ	1	160
Duwamish River (1)[c]	2050	NQ	2	480
Hylebos Waterway (1)[c]	3054	150	80	1210
Brown's Point (1)[c]	335	2	20	290
Budd Inlet (1)[c]	226	NQ	1	340
Case Inlet (1)[c]	134	5	NQ	1380

a   Numbers in parantheses indicate number of samples taken.

b   Data from Clayton, 1975 (zooplankton).

c   Data from Malins et al., 1980 (benthic shrimp).

d   Mean concentrations and standard deviation.

e   A dash indicates no data were collected.

f   NQ indicates that levels were not quantifiable.

TABLE IX-8

MEAN CONCENTRATIONS OF PCBs, CBDs, HEXACHLOROBENZENE (HCB),
AND 3- TO 5-RING ARENES IN ENGLISH SOLE LIVERS FROM REGIONS
OF PUGET SOUND.[a]

Sampling Location	Concentrations, ng/g dry weight			
	PCB	CBD	HCB	3-5 Ring Arenes
Elliott Bay				
Duwamish River (1)[b]	35290	3	20	110
South Bay (3)	19170+11230[c]	4+5	13+6	NQ
Seattle Waterfront (1)	9210	12	20	NQ
Magnolia Bluff (2)	3470	NQ[d]	10	NQ
Eastern Main Basin (2)	2335	3	7	NQ
Port Madison (1)	2970	4	10	NQ
Sinclair Inlet (1)	8550	3	10	NQ
Commencement Bay				
Hylebos Waterway (5)	15140+3830	3200+3373	1850+1200	430+490
Outside of Hylebos (3)	9827+5608	115+136	110+142	880+1510
Southwest Bay (1)	4960	10	60	NQ
Brown's Point (1)	6350	10	120	NQ
Budd Inlet (1)	1920	12	10	NQ
Case Inlet (1)	1600	5	10	50

a   Data from Malins et al., 1980.

b   Number in parentheses indicate number of samples taken.

c   Mean and one standard deviation.

d   NQ indicates levels were not quantifiable.

While the data are more limited, the levels of the other contaminants tended to exhibit similar spatial trends as the PCBs. Very low levels of CBDs and hexachlorobenzene were observed in all areas sampled except the Hylebos Waterway. Similarly, the concentrations of arenes in the shrimp, represented in Table IX-7 as the sums of the polynuclear aromatic hydrocarbons containing from 3 to 5 rings, tended to be higher in the areas having high levels in the sediments, but not to the extent exhibited by the PCBs. In fact, the highest concentrations were observed in Case Inlet, while the Budd Inlet sample showed higher levels than the sample from Elliott Bay. These data seem to reflect greater variability of analytical and/or natural origin, e.g., from differences in the species sampled at the different sites, and do not establish a strong regional dependence for the residue levels.

Table IX-8 presents data for the concentrations of the trace organic contaminants observed in the livers of English sole. These fish are bottom dwellers and feeders and the concentrations of PCBs clearly correspond to the levels in the sediments from the sampled areas. The highest concentrations were observed in the Duwamish River and Hylebos Waterway and the levels decrease fairly regularly away from these areas in both Elliott and Commencement Bays. Concentrations observed in the less urbanized areas, Port Madison, the stations from the east side of the main basin, and Budd and Case Inlet, were similar to each other with slightly lower levels in the Southern Sound samples.

The sole liver samples, however, also exhibited considerable variability among samples. For example, concentrations of PCBs in samples from the Hylebos Waterway ranged from 9690 ng/g to 20200 ng/g (on a dry weight basis). The differences may result from analytical variability, variability arising from natural differences among individual fish (discussed below), or may reflect some migration of the populations among areas of varying contamination.

As with the zooplankton and shrimp, the concentrations of PCBs observed in the sole livers exhibited a relatively smaller range than observed in the sediments. In the case of the sole, however, this may reflect movement of the sampled individuals throughout an area, e.g., the Duwamish River/southern Elliott Bay, and hence exposures corresponding to the average concentrations in the sediments from that area.

The concentrations of CBDs and hexachlorobenzene exhibited similar trends in the sole livers as observed in the shrimp. The concentrations were generally low and uniform except in the samples from the Hylebos Waterway. In the latter area, the concentrations ranged from 820 ng/g to 9080 ng/g for CBDs and from 840 ng/g to 3750 ng/g for hexachlorobenzene. The levels of the two components were strongly correlated.

An exception to the general trend of decreasing concentrations away from urban areas was one sample obtained from the north side of Brown's Point (Commencement Bay). This sample of sole liver contained relatively high concentrations of hexachlorobenzene (120 ng/g) compared to other open-Sound samples (generally about 10 ng/g). High concentrations of PCBs were also noted in this sample, while relatively high levels of both PCBs and hexachlorobenzene were observed in other fish species collected at this site (rock sole, pacific staghorn sculpin and quillback rock fish; Malins et al., 1980). These data seem to indicate either a local source, migration of the fish from more contaminated areas in the bay, or transport of contaminants along the northwest side of the bay and around Brown's Point. The latter mechanism appears most likely in light of what is known about the movement of water in Commencement Bay and the trends in the concentrations of organic contaminant residues in the fish samples which showed decreasing levels from the Hylebos Waterway along this trajectory.

Spatial trends in the concentrations of arenes in the English sole livers could not be established because these compounds were quantifiable only in samples from the Duwamish River and in or near the Hylebos Waterway. The lack of determinant levels in the majority of the samples probably reflects metabolism of the arenes (Malins et al., 1980). The samples with resolvable arenes did correspond to areas of high contamination and also contained high concentrations of PCB, CBD and hexachlorobutadiene.

The concentrations of PCBs, CBDs, hexachlorobenzene and arenes have been examined in a number of other organisms from Puget Sound, including crab, polychaetes, bivalves, rock sole, Pacific staghorn sculpin, quillback rockfish, and Pacific tom cod (Malins et al., 1980); and the levels of PCBs (and DDE) have been measured in sculpin, mussels, fish, harbor seals, and birds (Mowrer et al., 1977; Calambokidis et al., 1978; Finger et al., 1978; Cummins et al., 1976). Those organisms which were sampled simultaneously in more than one area exhibited the same spatial distributions of higher levels in the urbanized areas and relatively uniform, lower concentrations in the Main Basin and undeveloped embayments.

In this regard, it should be noted that the concentrations of PCBs in the blubber of harbor seals (Table IX-9) were observed to be similar in populations from Hood Canal, from the San Juan Islands and other northern Washington sites, and from Grays Harbor and other Washington coastal sites. Their similarity appears to substantiate the uniformity noted earlier of PCB levels in the environment away from the urbanized areas, including open ocean areas. The high levels observed in the Gertrude Island (Carr Inlet) and Southern Sound seals would appear to reflect feeding on organisms from contaminated areas, probably Commencement Bay. Concentrations of PCBs in fish eaten by seals from the Southern Sound did not appear to be higher than the levels observed in fish in Hood Canal, although the data were limited (Calambokidis et al., 1978).

TABLE IX-9

CONCENTRATIONS OF PCBs IN THE BLUBBER OF HARBOR SEALS FROM
PUGET SOUND AND OTHER PACIFIC NORTHWEST SITES.[a]

Collection Site	PCB Concentrations μg/g wet weight
Gertrude Island (11)[b]	171 ± 81
Other South Sound Sites (9)	171 ± 162
Hood Canal (9)	31 ± 36
Northern Washington Sites (9)	15 ± 9
Grays Harbor (28)	19 ± 15
Other Washington Coastal Sites (6)	16 ± 11

a   Data from Calambokidis et al., 1978.
b   Numbers in parentheses indicate number of samples taken.

Accumulation Mechanisms

Studies from Puget Sound indicate a range of probable mechanisms
controlling the concentrations of organic contaminants in the biota.
These studies are based on PCBs. In one study, the concentrations of
PCBs in zooplankton (copepods, euphausiids and ctenophores) were analyzed
as functions of a variety of habitat and physiological variables
(Clayton, 1975; Clayton et al., 1977).

In this study, only the percent of lipid in the organisms yielded a
significant correlation to PCB concentrations on a fresh weight basis.
When normalized to the lipid weight, the data yielded roughly linear
correlations between the concentrations of PCBs in the water and in the
organisms. The relative accumulation was greater for the more chlori-
nated PCBs. Similar behavior was noted in studies of the depuration of
PCBs by Mytilus edulis (Calambokidis et al., 1979). Mussels collected
from the Duwamish Waterway were caged and placed in Eld Inlet (Southern
Sound). The high levels of PCBs originally present in these mussels
decreased logarithmically with time of exposure to the cleaner environment
of Eld Inlet. More highly chlorinated PCB isomers were retained longer,
with depuration half-lives estimated to range from 3 days for 2- and
3-chloro components to 50 days for 6- and 7-chlorobiphenyls.

Conversely, the concentrations of PCBs in harbor seal blubber were found to increase with the age of the individuals within the populations from the sampled regions of the Sound and the Washington Coast (Table IX-10) (Calambokidis et al., 1978). The concentrations in the blubber were greater than observed in the fish species known to provide food of the seals even when the latter levels were normalized to a lipid weight basis. No major change in the relative concentrations of the different PCB components were noted between the seals and the food fish.

TABLE IX-10

PCB CONCENTRATIONS, $\mu g/g$, WET WEIGHT

| Age Group | Population | | |
	Gertrude Island	Hood Canal	Grays Harbor
Adult	243 + 32	93 + 11	22 + 15
Subadult	178 + 77		20 + 13
Pup	88 + 46	13 + 9	3.3 + 1.0

The data for these two types of organisms can be interpreted within a single coherent framework similar to the mechanistic model developed by Thoman (1978), in which the accumulation of the PCBs can be seen as a balance between the intake rate, the storage capacity of the organism, and the elimination rate. For smaller organisms, such as the zooplankton, the data indicate that the PCB residues are capable of facile exchange between the surrounding water and the internal sorption sites, primarily lipids. Residues may be accumulated from food, but the facile exchange results in the equilibration of the residue levels in the organisms with the levels in the surrounding water. The ultimate body burden thus reflects essentially a partitioning of the residues between the lipid and water phases.

The partitioning with the lipids tends to explain a large part of the variations in the body burdens both among species and spatially and temporally among the same or similar species. Some illustrative data from Puget Sound are presented in Table IX-11. In the first part of the table, comparison between two temporally different populations of zooplankton (both dominated by copepods and euphausiids) from Whidbey Basin showed that while fresh weight residue levels varied by nearly a factor of ten, normalization to lipid weight eliminated much of this difference. Similarly, comparisons of levels among different taxa when based on lipid weight exhibit lower variability than when compared on a fresh weight basis. There also appeared to be a trend of higher PCB concentrations in the lipids of fish with low lipids content, which may result from some sorption to non-lipid rich tissue.

TABLE IX-11

COMPARISONS OF THE CONCENTRATIONS OF PCBs IN SELECTED
ORGANISMS BASED ON WET WEIGHT AND LIPID WEIGHT

| Taxa | % Lipid | PCB CONCENTRATIONS | |
		Wet Weight, μg/g	Lipid Weight, μg/g
Zooplankton, Nov '73[a]			
Whidbey Basin (7)[b]	6.6 ± 1.2	0.288 ± 0.078	4.44 ± 0.67
Zooplankton, July '75[a]			
Whidbey Basin (5)	1.1 ± 0.3	0.031 ± 0.015	2.69 ± 0.73
Southern Sound Fish, Nov '77[c]			
Herring muscle (1)	19.9	0.859	4.31
Pile Perch (1)	13.7	0.304	2.22
Shiner Perch (1)	12.2	0.293	2.41
Tomcod (1)	3.8	0.224	5.83
English Sole (1)	2.31	0.154	6.66
Surf Smelt (1)	1.64	0.164	9.99
Pacific Staghorn Sculpin (2)	1.18	0.086	7.22
Starry Flounder (1)	1.06	0.097	9.11
Hood Canal Fish[c]			
Plainfish midshipman (1)	4.14	0.319	7.70
Pacific Staghorn Sculpin (1)	1.65	0.096	5.82

a   Data from Clayton, 1975.
b   Numbers in parentheses refer to the number of samples.
c   Calambokidis. et al., 1978.

At the other end of the scale, larger organisms do not have as great an exchange surface relative to their body volume. This is particularly true for the marine mammals which do not have gills, an effective exchange organ in fish. For these organisms, exchange with the surrounding water probably is considerably less important than is intake of PCBs from food and elimination primarily with excretia. Since elimination via the latter route is relatively inefficient, e.g., seal scat were found to have about the same PCB levels as observed in the food fish on either a wet weight or lipid weight basis (Calambokidis et al., 1978), some portion of the PCB residues in the food is retained. Thus the concentrations in the animal tends to increase with age, reflecting the consumption of greater quantities of food.

According to the size dependent model (Thoman, 1978), between the two extremes of equilibration and food chain transfer, there exists a continuum of relationships, primarily dependent on the size of the organisms. This continuum shifts as a function of increasing size of the organisms from the dominance of facile sorptive/desorptive equilibrium exchange to dominance by food intake and reduced elimination rates relative to the rate of accumulation.

However, it must be noted that due to the limited data, this model cannot be considered entirely validated for Puget Sound. The following points need to be considered:

1. The range of concentrations of PCBs in the water observed to be in equilibrium with the zooplankton was very limited. As a result, the linear dependence on the water concentration was poorly established (Clayton, 1975).

2. While the residue levels have been measured in a variety of organisms, systematic studies of the accumulation in organisms of intermediate size between zooplankton and seals have not been performed. Therefore, the existence of a size dependent shift from sorption to food intake dominance cannot be assured. In particular, it is not clear how much importance must be placed on the fact that seals are air breathing and do not have gills and hence do not have a major exchange site.

Applying this model to different organic compounds involves the same energetic considerations discussed for sorption onto the suspended particulate matter. As a result, in organisms for which direct sorptive exchange is most important the internal residues will reflect in general preferential accumulation of the less soluble compounds. This trend was observed for PCBs in zooplankton, where the relative accumulation of residues was in the order hexachlorobiphenyl> penta->tetra (Clayton, 1975). Similarly, in the more recent data, the detected CBDs were predominantly

penta- and hexachloro-isomers, while the arenes were predominantly the multi-ring compounds (Malins et al., 1980). Specific information for a number of other compounds has been reviewed recently (Callahan et al., 1979). These data are primarily for freshwater systems and for areas other than Puget Sound, and therefore their direct relevance is unknown. In general, the relationships fit the pattern outlined above.

SUMMARY

In comparison with the research on trace metals in Puget Sound, investigation of organic contaminants has only begun. This study is undeniably a formidable and extremely complex task when one recognizes that literally thousands of anthropogenic organic compounds can reasonably be considered likely components of the present and future marine environment. Neither convenient, inexpensive analytical techniques for monitoring this host of contaminants nor the toxicological information to even estimate their potential hazards to resident biota and their consumers are available.

At the present time, in excess of 200 organic compounds considered to be toxic have been identified in the water, sediment or biota of Puget Sound, and/or in effluents discharging to the Sound. Very few of these compounds have received even limited systematic study to determine spatial distributions, levels in resident organisms or their dominant sources.

Those compounds for which a significant amount of data has been acquired, principally PCBs and arenes, show considerable similarities in the overall spatial distributions to the trace metals. Very high concentrations in the sediment and biota have been observed in the industrialized embayments of Elliott and Commencement Bays and Sinclair Inlet. In contrast to the metals, however, the ubiquitous "background" levels of the anthropogenic organic contaminants which are observed in all non-developed areas of the Sound are not natural, but rather appear to reflect the result of the rapid and complete dispersion of water-borne contaminants by the currents in the Sound.

To what extent other organic compounds exhibit the same distributions is presently unknown. It can be conjectured that large differences may exist, particularly since the many organic contaminants are used in commerce in specific, limited applications in one or a few industrial processes. As a result, sources to the Sound for many compounds may be spatially limited and hence gross contamination largely limited to specific areas. For example, the sources (unidentified) and hence the major incidences of contamination of the Sound by chlorinated butadienes appear to be largely confined to areas of Commencement Bay.

The uptake of organic compounds by resident organisms has received some study which indicates a strong correspondence of the tissue concentrations with the levels observed in the sediments from the same areas for many organisms. The body burden, however, has been shown to be a complex function of the levels in the ambient environment, the amount consumed in the organisms' food, and the rates of excretion and metabolism. For smaller organisms, facile sorptive-desorptive exchange with the ambient concentrations appears to dominate for most strongly accumulating compounds, e.g., PCBs. At least for some larger organisms, the excretion rate is very slow and thus, for example, in harbor seals from Puget Sound, concentrations of PCBs in the body fat were observed to increase with age of the fish, apparently reflecting continued accumulation without comparable elimination.

All of the processes, however, are variable among compounds and among the organisms. For example, PCBs and many of the arenes exhibit similar tendencies for accumulation, as indicated by similar sorption to particulates from water. However, the concentrations of PCBs observed in demersal fish livers was invariably much greater than the concentrations of arenes. These differences were considered to reflect the selective metabolism and thus elimination of the arenes.

Thus, while the data in general support a conclusion that the exposure (dose) levels of the different organic compounds to the biota probably correspond strongly with the concentrations in the abiotic environment, the concentrations measured in the tissues may not reflect this exposure due to differences in accumulation and/or metabolism rates. In addition, it should be noted that metabolism and detoxification are not necessarily synonymous. For example, it has been shown to be the metabolites of benzo(a)pyrene, an arene, not the parent compound, which are carcinogens in animals. As discussed in Chapter X, no effects on the resident organisms or their consumers have been unequivocally related to any organic contaminant. However, the spatial distribution of the incidences of a number of abnormalities has been observed to be coincident with the areas of high organic contamination. While recent temporal trends have not been firmly established for any compound, there is some evidence that at least the concentrations of PCBs are diminishing in Puget Sound. It must be hoped that present and future environmental awareness and regulatory activities will be effective in controlling the entry of hazardous organic contaminants to the Sound. At the same time, it must be recognized that many of the substances are resistant to degradation and will persist for some time even after all sources are eliminated.

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CHAPTER 10.   BIOLOGICAL MALADIES

INTRODUCTION

It is difficult to establish cause and effect relationships between exposure to environmental contaminants and resultant pathological effects when dealing with free-living populations. This difficulty has repeatedly been encountered by epidemiologists trying to elucidate human environmental diseases and is similarly encountered by epizootiologists studying animal diseases. The problems arise through variations in genetic history in a wild population, as well as variations in nutritional status, duration of exposure, route of exposure, age, sex, etc. For these reasons, the majority of the information available on toxic injury has been developed through short or long term bioassays conducted under laboratory conditions.

A voluminous literature describing acute and chronic effects of toxicants on aquatic/marine organisms has developed over the years; however, almost no information is available on naturally occurring lesions which are directly attributable to intoxication. Similarly, within the Puget Sound region a number of pathological conditions have been identified which may occur with increased frequency in contaminated areas, but clear evidence establishing their cause has not been forthcoming. As a general observation it should be noted that no overt perturbations in any Puget Sound population have been documented which can unequivocally be related to chemical stress. At the present time, the impact of human activities results primarily from physical alteration of habitats and harvesting of commercially important food organisms.

The paucity of information and sitings may be due in part to the silence of mortalities and morbidities occuring in nature. Unlike the situation in hatcheries where every dead animal is easily visible, the situation in the wild is imperceptible. Dead organisms are quickly scavenged and moribund or handicapped individuals become easy prey. Further obscuring the problem is the vastness of the body of water inhabited by the organisms. It is only through repetitive, directive sampling that abnormalities will be detected; unfortunately, the cost of such baseline studies make them prohibitive to the majority of investigators.

In addition to miscellaneous reports which might relate to pollution, four major anomalies in Puget Sound organisms have been tentatively linked by investigators to environmental factors. These conditions include the following: fin erosion, epidermal papilloma, hepatoma and

other liver abnormalities and pseudobranchial neoplasms. All four conditions have been observed in fish; no anomalies of similar epizootic distribution have been observed among invertebrates to date.

In this chapter, we will discuss the major lesions reported among Puget Sound organisms and also mention a few other studies which have attempted to document pollution-related effects.

FISH DISEASES

Fin Erosion

Background: Fin erosion* is a disease of demersal marine fishes characterized by the loss of fin tissue which proceeds from the margin of the fin toward the body. Both soft tissue and the fin rays are affected by conditions such as ulceration, hyperpigmentation, deformation and scarring. Loss of a mucous secreting ability (Sherwood, 1978) is also common in affected fish and is believed to reduce their first line of defense against invading organisms.

Although numerous bacteria have been isolated from affected fish from a variety of geographic locations, no single organism or group of organisms has been consistently associated with this disease. Likewise, no evidence for viral or fungal association has been found (Staude, 1979; Miller et al., 1977).

Geographically this disease has been reported from numerous locations around the world (Sherwood, 1978), all of which have some association with toxic waste discharge (Table X-1). Three areas

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* Histologically, fin erosion is characterized by a chronic fibrosing condition accompanied by epidermal hyperplasia, proliferation of fibroblasts, and resorption of fin rays. The hyperplasia results in a 2- to 3-fold increase in epidermal cells with a corresponding increase in thickness. The cells maintain a basically normal morphology during this growth phase, although individual epithelial cells have been observed to undergo degenerative changes (Miller et al., 1977). Proliferation of fibroblasts, a recognized reaction to cellular injury, is also accompanied by sclerosing of small blood vessels in the fin web as well as perineural fibrosis of small peripheral nerves. Fin ray resorption is characterized by replacement of the ray by fibroblastic tissue and collagen. These deformed fins also are infiltrated by mononuclear cells which are scattered focally throughout the scar tissue.

TABLE X-1

FIN EROSION IN DEMERSAL FISHES FROM VARIOUS
COASTAL AREAS (Sherwood, 1978)

Location	Some Affected Species	Reference
Southern California nearshore waters	Microstomus pacificus (Dover sole) Glyptocephalus zachirus (rex sole) Lyopsetta exilis (slender sole) Sebastes elongatus (greenstriped rockfish) Sebastes miniatus (vermilion rockfish)	Mearns and Sherwood, 1974 Sherwood and Mearns, 1977
Duwamish River Waterway, Puget Sound	Platichthys stellatus (starry flounder) Parophrys vetulus (English sole)	Wellings et al., 1976
Sandy Hook/ Raritan Bays; Apex dumping area, New York Bight	Pseudopleuronectes americanus (winter flounder)	Murchelano and Ziskowski, 1976
Boston Harbor, Mass.	. Pseudopleuronectes americanus (winter flounder)	Charles A. Willingham Battelle Columbus Laboratories, Duxbury, Mass., personal communication
Northeast Irish Sea	Pleuronectes platessa (plaice) Limanda limanda (dab)	Perkins et al., 1972
Suruga Bay, Japan	Uranoscopus japonicus (Japanese stargazer)	Nakai et al., 1973

within the United States have been most intensely studied and the data suggest that fin erosion in these areas results from exposure to a common component related to toxic discharges (Sherwood and McCain, 1976). Evidence for this conclusion stems from the following observations: 1) prevalence of the disease was elevated in waste-receiving areas, 2) no inflammatory response was associated with the condition, 3) no pathogenic organisms were associated with the lesions, and 4) the

species most severely affected had extensive association with bottom sediment (Sherwood and McCain, 1976). Further evidence incriminating bottom sediments comes from the fact that demersal fishes were most commonly affected and the fins of these species which contact the sediment were most frequently eroded (Sherwood and Mearns, 1977; Sherwood, 1978).

Observations and experiments in areas other than Puget Sound have shown a high correlation between the frequency of occurrence of fin erosion and the discharge of municipal wastewater (Sherwood and Mearns, 1977). The majority of species affected in this study belonged to either the flatfish or rock fish families with infrequent incidences observed in 11 other families.

Attempts to experimentally reproduce fin erosion in the laboratory by mimicking naturally occurring conditions have shown some promise. Early signs of fin erosion were observed in dover sole exposed to contaminated sediment for 13 months (Sherwood, 1976). These lesions resembled those found in wild fish caught in an affected area in southern California. It was suggested that elevated levels of PCBs might be correlated with increased frequency of fin erosion, but the evidence was mostly circumstantial (Sherwood, 1976; Sherwood, 1978).

Incidence in Puget Sound: As a result of the high levels of many pollutants in the Duwamish River, this area has been studied extensively in comparison to other areas of the Sound. The following discussion relates primarily to fish observed in this area. Table X-2 shows the occurrence of fin erosion by month and by fin in the starry flounder. Overall the dorsal fin was the most frequently affected, although all fins were involved to some degree.

The incidence of fin erosion was highest during winter and early spring and lowest in late spring and summer of 1975-1976 (Miller et al., 1977). The authors attributed this difference to a decrease in the abundance of starry flounder in the river in the summer. No fin erosion was observed near the sewage outfalls at West Point or Alki Point, or at the reference site, Point Pully, during this study. The majority of fish affected were larger than 150 mm total length representing two and three year old fish. The incidence of fin erosion increased with both size and age (Table X-3) and was confined to fish caught in the middle and upper Duwamish River stations.

Attempts to experimentally reproduce fin erosion using Duwamish River sediment were inconclusive. Two of 30 experimental English sole developed lesions after one month, while none of the controls showed signs of disease. Starry flounder exposed under identical conditions showed no lesions per 10 fish (Miller et al., 1977).

TABLE X-2

OCCURRENCE OF FIN EROSION BY MONTH AND BY FIN ON INDIVIDUAL STARRY
FLOUNDER (PLATICHTHYS STELLATUS) COLLECTED IN THE DUWAMISH RIVER DURING 1975-1976.
(from Miller et al., 1977)

Month and Year	Dorsal	Anal	Caudal	Eyed pectoral	Blind pectoral	Eyed pelvic	Blind pelvic	Number of fish afflicted
February 1975	20	15	6	0	1	0	0	32/256
March 1975	29	12	9	0	8	4	2	33/185
April 1975	5	5	2	1	2	1	0	8/73
May 1975	29	12	9	0	8	4	2	29/213
June 1975	2	0	0	0	0	0	0	2/53
July 1975	2	1	1	0	0	0	0	3/34
August 1975	3	2	2	0	0	0	0	4/30
September 1975	10	13	4	0	1	0	1	20/55
October 1975	13	8	3	0	3	1	0	17/315
November 1975	4	3	2	0	0	1	1	4/97
January 1976	3	2	1	0	0	0	0	3/46

TABLE X-3

PERCENT INCIDENCE BY MONTH OF FIN EROSION ON STARRY FLOUNDER
(PLATICHTHYS STELLATUS) COLLECTED IN THE DUWAMISH RIVER DURING
1975-1976 (from Miller et al., 1977)

Total length (mm): Date	50-99	100-149	150-199	200-249	$\geq$ 250
February 1975	0.0 (0/13)	7.6 (5/66)	15.2 (14/92)	13.3 (10/75)	30.0 (3/10)
March 1975	0.0 (0/0)	8.2 (5/61)	14.4 (14/97)	52.0 (13/25)	50.0 (1/2)
April 1975	0.0 (0/0)	10.0 (4/40)	12.5 (3/24)	12.5 (1/8)	0.0 (0/1)
May 1975	0/0 (0/0)	0.0 (0/111)	20.4 (11/54)	17.5 (7/40)	50.0 (4/8)
June 1975	0.0 (0/0)	0.0 (0/15)	0.0 (0/16)	11.1 (2/18)	0.0 (0/4)
July 1975	0.0 (0/0)	0.0 (0/9)	16.6 (2/12)	0.0 (0/10)	33.3 (1/3)
August 1975	0.0 (0/0)	0.0 (0/10)	0.0 (0/14)	66.6 (4/6)	0.0 (0/0)
September 1975	0.0 (0/1)	0.0 (0/5)	23.1 (3/13)	57.1 (16/28)	5.5 (1/8)
October 1975	0.0 (0/90)	0.9 (1/110)	9.4 (8/85)	26.6 (8/30)	0.0 (0/0)
November 1975	0.0 (0/13)	7.4 (2/27)	2.6 (1/38)	0.0 (0/19)	0.0 (0/0)
January 1976	0.0 (0/7)	0.0 (0/17)	0.0 (0.12)	30.0 (3/10)	0.0 (0/1)

Fin erosion studies have been conducted comparing the incidence of the malady off Los Angeles, where dover sole were most frequently affected, and near Seattle, where the starry flounder were the most severely affected (Sherwood and McCain, 1976). Comparisons of the concentrations of total PCB, DDE, cations (calcium, potassium, magnesium, and sodium) and trace metals were made between the two geographic areas and between diseased and non-diseased fishes (Sherwood and McCain, 1976). Only elevated levels of PCB could be shown to correlate with the incidence of the disease in both species from both areas (Table X-4). The correlation was not statistically significant.

Similarly, in other studies in Puget Sound, elevated levels of PCBs were found in the livers of affected fish (Table X-5) compared to unaffected fish from the Duwamish River and to fish from a control site. DDE and metals showed no correlation with fin erosion at either site. Another comparative study (Sherwood, 1977) demonstrated that starry flounder from the Duwamish had elevated levels of silver and depressed levels of cadmium, copper, and zinc than did control fish. No similar relationships among comparable fish from Southern California were observed.

Epidermal Papilloma

The occurrence of epidermal papillomas in flatfishes along the Pacific Coast of North America was noted as early as the late 1800's by fishermen in the Gulf of Alaska. Subsequent descriptions of these lesions were published by Schlumberger and Lucke (1948) and by Nigrelli et al. (1965); however, it was not until the 1960's that extensive research into their characterization was undertaken, principally by Wellings and Chuinard (1964).

The epidermal papillomas found in flatfishes are seen as three distinct morphological types described by Wellings et al. (1965), as an angioepithelial nodule, an angioepithelial polyp, and an epidermal papilloma. The angioepithelial nodules* are small (1 to 2 mm), circumscribed, sessile nodules that occur over the entire body surface. The angiomatous component shows possible invasive tendencies because of extension into skeletal muscle. These nodules are not observed on fish

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* Histologically, the nodules are seen to be composed of proliferative vascular endothelial cells having a uniformly acidophilic, granular cytoplasm and small pleomorphic nuclei. The epithelial cells generally have a normal and uniform appearance; however, there are a few cells with enlarged nuclei, prominent nucleoli, and irregular cytoplasmic staining.

TABLE X-4

CHLORINATED HYDROCARBONS IN THE MUSCLE,
LIVER, AND BRAIN OF DOVER SOLE FROM SOUTHERN CALIFORNIA
AND STARRY FLOUNDER FROM WASHINGTON WITH AND WITHOUT ERODED
FINS. (from Sherwood and McCain, 1976)

	Total PCB, mg/kg		pp-DDE, mg/kg	
	Dover Sole	Starry Flounder	Dover Sole	Starry Flounder
High-Disease-Prevalence Area[a]				
No apparent fin erosion				
Muscle	0.159	0.591	1.34	0.008
Liver	3.69	11.9	43.3	0.213
Brain	0.978	0.916	2.92	0.008
Moderate to severe fin erosion				
Muscle	1.82	0.508	23.2	0.007
Liver	18.7	18.8	211	0.013
Brain	1.43	2.14	7.37	-*
Control Area[b]				
No apparent fin erosion				
Muscle	0.047	0.112	0.038	0.006
Liver	0.355	0.530	0.519	0.035
Brain	0.672	0.311	0.275	0.032

a   High-disease prevalence areas were the Palos Verdes shelf (Los Angeles) for the southern California samples and the Duwamish River for Puget Sound.

b   Control areas were Dana Point (near San Clemente) in southern California and the Nisqually River estuary in Puget Sound.

* Below the limit of detectability

TABLE X-5

PCB CONCENTRATIONS (AROCLORS 1242, 1254, and 1260) IN PPM WET WEIGHT FOR STARRY
FOUNDER TAKEN FROM THE DUWAMISH RIVER AND McALLISTER CREEK. Each sample value
represents a composite of tissues taken from three fish (from Miller et al., 1977).

Tissue Source	McAllister Creek control				Duwamish River No fin erosion				Duwamish River Fin erosion			
	A-1242	A-1254	A-1260	Total	A-1242	A-1254	A-1260	Total	A-1242	A-1254	A-1260	Total
Liver	0.04	0.26	0.23	0.53	1.63	5.97	4.29	11.89	1.03	7.61	9.13	18.77
Muscle	0.08	0.01	0.02	0.11	0.08	0.27	0.23	0.59	0.06	0.17	0.27	0.51
Skin (blindside)	0.03	0.03	0.05	0.11	*	*	*	*	0.66	2.49	1.78	4.94
Gonad	0.02	0.02	0.05	0.08	0.09	0.18	0.10	0.37	0.05	0.19	0.14	0.38
Brain	0.07	0.03	0.21	0.21	0.08	0.41	0.42	0.92	0.27	1.32	0.55	2.14

*Analysis not performed

over one year of age. The angioepithelial polyps* are large, soft, sharply demarcated sessile lesions. The polyps are larger than the nodules and are seen usually in fish over one year of age. The epidermal papillomas** are large (1 to 6 cm) cauliflower-like proliferative lesions. The central portion of the tumor is frequently a raised wart-like structure, while the edges often are flat and grade into the surrounding tissue. They do not appear to be invasive.

An unidentified, tumor-specific cell, designated as an "X-cell," has been described in all three types of lesions (Brooks et al., 1969). These hypertrophic cells have a large nucleus and prominent nucleolus. They have numerous dense cytoplasmic granules and lack intercellular bridges. The cells have a thick extracellular coat and they are frequently found in groups of two, three and four. The X-cells are seen as small cells in the dermis of angioepithelial polyps and epidermal papillomas (McArn and Wellings, 1971). It is not known whether these are fish cells or foreign cells.

McArn et al. (1968) feel that the three types of proliferative lesions are histogenetically related in that the tumors begin as angio-epithelial nodules and become either angioepithelial polyps or epidermal papillomas. Kelly (1971) feels that both of the angiomatous stages are inflammatory rather than being new tissue growths (neoplastic), and represent a reaction either to the X-cells or to some other exogenous irritant. Most workers have felt that the tumors lead to decreased survivability, since they are not seen in older age classes, but Kelly (1971) has stated that the tumors slough off in time and that the epidermis is regenerated.

Papillomas endemic to certain populations also have been described in croakers (Russel and Kotin, 1957), catfish (Lucke and Schlumberger, 1941), gobies (Kimura et al., 1967), eels (Deys, 1969), and smelt (Dawe and Harshbarger, 1975) and their occurrence has been related to the presence of pollutants from industrial and/or domestic sources.

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* Histologically, the polyps consist primarily of vascular connective tissue identical to the stromal tissue of the angioepithelial nodule. They are covered by normal or slightly hyperplastic epithelium that may be thrown into folds. Some of the epithelial cells are enlarged and pleomorphic.

** Histologically, there are prominent papillary folds of hyperplastic epithelium and an inconspicuous dermal component. The epithelial cells are of generally uniform size and ovoid to polygonal in shape. They have an elevated nuclear-cytoplasmic ratio compared to normal cells and show increased nuclear pleomorphism, prominent nucleoli, and variable cytoplasmic staining.

Three generalizations have been made about cutaneous papillomas in these fishes: 1) they most frequently occur in bottom feeding species; 2) they have focal geographic distribution; and 3) the distribution is usually associated with urbanization and industrialization (Dawe and Harshbarger, 1975). All of these factors suggested the presence of one or more environmental agents was inducing the malady.

The distribution of papillomas in flatfish has been reported to be geographically focal as well, with highest incidences occurring near heavily industrialized areas (Cooper and Keller, 1969; Miller and Wellings, 1971). This focal distribution suggests that the fish may indeed be exposed to some type of chemical pollutant that is present in varying quantities throughout a given body of water.

In recent studies (Miller et al., 1977) conducted at two sewage outfalls and one control site within Puget Sound, the incidence of tumor-bearing English sole varied primarily as a function of season and age (Tables X-6, X-7, and X-8). Tumor-bearing age group 0 (young-of-the-year) fish were generally not seen before September and the incidence of tumors in this age group peaked during September to December. Age group I fish had generally higher frequencies of tumors which did not show strong seasonal trends. Group II and older fish exhibited few tumors. Overall, the incidence in age 0 fish varied from 4.98 percent (Point Pully) to 2.39 percent (Alki Point) and 2.13 percent (West Point), and was considered to be statistically higher at Point Pully than at either of the other stations. Similar differences were seen in age group I fish (Point Pully, 9.27 percent; Alki Point, 8.36 percent; West Point, 4.54 percent) but were statistically different only between Point Pully and West Point.

During this study the average incidence of papillomas in starry flounder was higher in the Duwamish River (16.9 percent) than that seen in English sole at the other three stations. The incidence was highest (44.7 percent) in young fish (50 to 99 mm total length) and decreased with the age of the fish. The papillomas occurred predominantly in fish collected in the upper stations of the river and were primarily on the eyed side of the body.

One interesting finding in a recent Puget Sound study (Miller et al., 1977) was the observation that the papillomas seen in the Duwamish River were primarily late-stage lesions rather than angioepithelial nodules. These findings suggest either that tumor-bearing fish migrate into the area or that they occur in other parts of the river which were not sampled. If this question could be resolved, it might shed light on the nature of the etiological agent(s).

A second interesting finding in this study was that, in comparison with data collected in 1969, the incidence of tumor in young-of-the-year fish was markedly increased: 40 percent in 1975-1976 versus 20.1 percent

TABLE X-6

PERCENT INCIDENCE OF TUMOR-BEARING ENGLISH SOLE
(PAROPHRYS VETULUS) COLLECTED AT WEST POINT DURING 1975-1976
(From Miller et al., 1977)

Month	Beach seine			Otter trawl		
	Age 0	Age I	Age II+	Age 0	Age I	Age II+
February	0.0 (0/10)	18.4 (7/38)	0.0 (0/40)	NO SAMPLING		
March	NO SAMPLING			0.0 (0/0)	8.7 (2/23)	0.0 (0.130)
April	3.2 (1/31)	100.0 (1/1)	100.0 (1/1)	0.0 (0/13)	2.5 (1/40)	0.0 (0/105)
May	0.0 (0/42)	0.0 (0/3)	0.0 (0/13)	0.0 (0/0)	20.0 (1/5)	0.0 (0/44)
June	0.0 (0/129)	0.0 (0/33)	0.0 (0/52)	0.0 (0/0)	3.2 (1/31)	0.0 (0/72)
July	0.0 (0/144)	0.0 (0/11)	0.0 (0/24)	0.0 (0/3)	0.0 (0/14)	0.0 (0/58)
August	0.0 (0/235)	7.1 (1/14)	0.0 (0/15)	0.0 (0/6)	0.0 (0/14)	0.0 (0/30)
September	0.0 (12/171)	17.6 (3/17)	0.0 (0/7)	7.7 (3/39)	2.5 (1/40)	0.0 (0/58)
October	4.2 (7/165)	3.3 (6/180)	0.0 (0/85)	6.3 (1/16)	2.6 (1/39)	0.0 (0/49)
November	7.8 (4/51)	0.0 (0/0)	0.0 (0/0)	0.0 (0/0)	0.0 (0/0)	0.0 (0/0)
December	9.5 (8/84)	10.4 (8/77)	0.0 (0/73)	NO SAMPLING		
January	0.0 (0/5)	5.7 (4/69)	0.0 (0/69)	0.0 (0/0)	25.0 (1/4)	0.0 (0/0)
February	0.0 (0/4)	4.1 (2/49)	0.0 (0/22)	0.0 (0/0)	1.5 (2/133)	0.8 (1/125)
March	0.0 (0/226)	0.0 (0/0)	0.0 (0/2)	0.0 (0/0)	0.0 (0/20)	0.0 (0/46)
April	0.0 (0/175)	0.0 (0/2)	0.0 (0/1)	0.0 (0/0)	3.1 (5/165)	0.0 (0/70)
May	0.0 (0/130)	0.0 (0/2)	0.0 (0/4)	0.0 (0/4)	0.0 (0/10)	0.0 (0/62)

TABLE X-7

PERCENT INCIDENCE OF TUMOR-BEARING ENGLISH SOLE
(PAROPHRYS VETULUS) COLLECTED AT ALKI POINT DURING 1975-1976
(From Miller et al., 1977)

Month	Beach seine			Otter trawl		
	Age 0	Age I	Age II+	Age 0	Age I	Age II+
April	0.0 (0/19)	0.0 (0/2)	0.0 (0/0)	0.0 (0/1)	33.3 (1/3)	0.0 (0/40)
May	NO SAMPLING			0.0 (0/0)	0.0 (0/15)	0.0 (0.29)
June	0.0 (0/29)	8.1 (3/37)	15.4 (2/13)	0.0 (0/0)	0.0 (0/3)	0.0 (0/17)
July	0.0 (0/90)	6.6 (2/30)	0.0 (0/2)	0.0 (0/0)	0.0 (0/14)	0.0 (0/22)
August	0.0 (0/30)	0.0 (0/0)	0.0 (0/0)	0.0 (0/0)	0.0 (0/4)	0.0 (0/9)
September	0.0 (0/9)	0.0 (0/11)	0.0 (0/0)	0.0 (0/2)	0.0 (0/10)	0.0 (0/35)
October	10.0 (2/20)	0.0 (0/0)	0.0 (0/18)	8.3 (1/12)	0.0 (0/3)	0.0 (0/6)
November	9.1 (4/44)	3.6 (1/28)	0.0 (0/39)	0.0 (0/0)	0.0 (0/0)	0.0 (0/7)
December	6.6 (4/61)	1.9 (2/106)	0.0 (0/98)	0.0 (0/0)	0.0 (0/0)	0.0 (0/3)
January	0.0 (0/1)	28.6 (2/7)	1.3 (1/80)	0.0 (0/0)	100.0 (1/1)	0.0 (0/33)
February	0.0 (0/2)	25.0 (2/8)	2.0 (1/51)	NO SAMPLING		
March	0.0 (0/0)	66.7 (2/3)	0.0 (0/2)	0.0 (0/0)	0.0 (0/37)	0.0 (0/122)
April	0.0 (0/37)	0.0 (0/0)	0.0 (0/2)	0.0 (0/0)	12.5 (4/32)	0.0 (0/147)
May	0.0 (0/35)	22.2 (2/9)	0.0 (0/13)	0.0 (0/0)	0.0 (0/2)	0.0 (0/54)
June	0.0 (0/68)	0.0 (0/4)	0.0 (0/0)	NO SAMPLING		

TABLE X-8

PERCENT INCIDENCE OF TUMOR-BEARING ENGLISH SOLE
(PAROPHRYS VETULUS) COLLECTED AT PT. PULLY DURING 1975-1976
(From Miller et al., 1977)

Month	Beach seine			Otter trawl		
	Age 0	Age I	Age II+	Age 0	Age I	Age II+
February	0.0 (0/9)	6.3 (3/48)	13.3 (2/15)	NO SAMPLING		
March	0.0 (0/2)	0.0 (0/2)	0.0 (0/2)	NO SAMPLING		
April	0.0 (0/7)	20.0 (1/5)	0.0 (0/0)	0.0 (0/1)	0.0 (0/10)	0.0 (0/41)
May	0.0 (0/8)	0.0 (0/7)	0.0 (0/13)	0.0 (0/0)	20.0 (4/20)	0.0 (0/31)
June	0.0 (0/60)	23.5 (8/34)	0.0 (0/45)	0.0 (0/0)	18.5 (5/27)	0.0 (0/57)
July	0.0 (0/145)	18.5 (12/65)	0.0 (0/44)	0.0 (0/0)	7.1 (2/28)	0.0 (0/15)
August	0.0 (0/343)	21.2 (11/52)	0.0 (0/8)	0.0 (0/0)	11.1 (1/9)	0.0 (0/17)
September	6.3 (13/207)	7.9 (10/126)	0.0 (0/45)	0.0 (0/3)	4.5 (1/22)	0.0 (0/36)
October	14.7 (50/340)	6.3 (9/144)	2.1 (2/97)	13.3 (2/15)	0.0 (0/13)	0.0 (0/7)
November	4.2 (1/24)	1.4 (1/71)	0.0 (0/102)	6.7 (1/15)	10.0 (3/30)	0.0 (0/15)
December	12.5 (2/16)	6.3 (2/32)	0.0 (0/106)	0.0 (0/6)	5.3 (1/19)	0.0 (0/32)
January	0.0 (0/0)	14.7 (5/34)	0.0 (0/42)	0.0 (0/0)	16.6 (1/6)	0.0 (0/35)
February	0.0 (0/0)	8.3 (1/12)	0.0 (0/10)	0.0 (0/0)	2.6 (1/38)	1.6 (1/60)
March	0.0 (0/3)	0.0 (0/0)	0.0 (0/0)	0.0 (0/0)	4.0 (1/25)	0.0 (0/50)
April	0.0 (0/6)	0.0 (0/0)	0.0 (0/6)	0.0 (0/0)	0.0 (0/4)	0.0 (0/60)
May	0.0 (0/67)	50.0 (1/2)	0.0 (0/21)	0.0 (0/0)	100 (1/1)	0.0 (0/22)
June	0.0 (0/106)	3.8 (2/52)	1.2 (1/81)	---	---	---

in 1969. The significance of these data is unclear since a high variability in the incidence of papillomas unrelated to pollution in starry flounder has previously been reported (McArn et al., 1968).

The variable occurrence of papilloma-bearing fish at all sites studied within Puget Sound makes a relationship between tumor prevalence and wastewater discharge questionable. Similar negative spatial correlations were obtained in California by Sherwood (1978) and in other Washington studies by Miller and Wellings (1971). A recent review of abnormalities in Puget Sound fishes by Malins et al. (1980) states that these epidermal lesions are probably not related to pollution. The possibility does persist, however, that even though a direct causal relationship between pollution and tumor occurrence has not been shown, pollution may increase the susceptibility of flatfish to the causitive agent and the tumors may thereby serve as indicators of water-borne pollutants (Miller and Wellings, 1971; Stich et al., 1976).

Liver Abnormalities

Hepatomas: Hepatomas (liver tumors) have been described in a variety of fish species. The most widely studied have been those of rainbow trout (Salmo gairdneri) induced by aflatoxin, a fungal metabolite (Halver and Mitchell, 1967). They also have been found in wild white suckers (Catostomus commersoni) (Dawe et al., 1964) and have been experimentally induced by exposing various species to known hepatocarcinogens such as dimethylnitrosamine, acetylaminofluorine, urethane, thiourea and p-dime-thylaminoazobenzene (Ashley, 1969; Halver and Mitchell, 1967).

Hepatomas have been found in two species of pleuronectids in Puget Sound: the starry flounder (Platichthys stellatus) and the English sole (Parophrys vetulus). The tumors did not occur randomly throughout the Sound but rather were concentrated within the Duwamish River estuary (McCain et al., 1977; Miller et al., 1977; Pierce et al., 1978). In addition, a variety of non-neoplastic liver abnormalities have been described in fish from the Duwamish River and from waters near sewage outfalls (Alki Point, West Point). The liver abnormalities were grossly recognizable as generalized hypertrophy and variable discoloration. These changes are consistent with those associated with toxic injury but are not characteristic pathological indicators of liver tumors.

The livers of some fish collected in the Duwamish River estuary showed, in addition to the aforementioned lesions, other more severe alterations. These include hyperplasia and hypertrophy of melanin macrophage centers, centrilobular vacuolation and necrosis, increased hepatocellular basophilia and hypertrophy often associated with bizarre nuclei and/or multiple nucleoli, perivascular fibrosis, intercellular melanin deposition and hepatoma formation.

The types of hepatomas noted were variable and have included proliferative lesions of both hepatocellular and biliary components. Most of the neoplasms were minimum deviation basophilic nodules* or eosinophilic nodules**. These two types of nodules were the ones most commonly encountered, but a variety of other types have been noted (Pierce et al., 1978).

The extent of enlargement as measured by somatic liver indices in livers from fish collected at Alki Point, West Point, Point Pully (control site) and the Duwamish River was reported by Pierce et al. (1978) to range from 1.12 percent + 0.20 percent (Point Pully) to 2.40 percent + 0.65 percent (Duwamish River), a difference of statistical significance.

Surveys conducted in 1975-1976 (Miller et al., 1977) showed detectable abnormalities in 22 percent of fish from Pt. Pully, 60 percent of fish from West Point, 90 percent of fish from Alki Point and 92 percent of fish from the Duwamish estuary. However, in spite of the frequency of liver disease in the vicinity of the two sewage outfalls, frank neoplasms were found only in Duwamish River fish where they occurred in an incidence of 32 percent.

The cause of hepatomas or of the hepatoses is unknown. In spite of the absence of supporting laboratory studies, the lesions appear to be similar to ones induced in fish by polychlorinated biphenyls and petroleum hydrocarbons (Cooper and Keller, 1969; Hansen et al., 1974; Johansson et al., 1972; Walsh and Ribelin, 1975).

Other Liver Abnormalities: The liver lesions found in a number of Puget Sound fishes were recently summarized by Malins et al., 1980. Target species were selected on the basis of three criteria: (1) wide distribution throughout Puget Sound, thus allowing comparisons

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* The basophilic nodules were comprised of cells with intensely basophilic cytoplasm which were large and pleomorphic. Their nuclei were hyperchromatic and often contain multiple nucleoli. Frequently the nodules were fibrotic with some evidence of central necrosis. In addition they were generally well demarcated and surrounded by a zone of compression atrophy.

** Eosinophilic nodules were characterized by eosinophilic cells which also were large and pleomorphic with hyperchromatic nuclei. These nodules were poorly demarcated from surrounding normal parenchyma and were frequently invasive. Two morphologic patterns were discernible, one comprised of many small cells, the other of relatively few large cells. Eosinophilic nodules generally were seen only in livers containing multiple types of hepatomas.

of one area with another; (2) life history stages associated with sediments, maximizing contact with contaminants, and (3) species previously reported to have pathologic conditions which could be caused by chemical contaminants. The species included the English sole (Parophrys vetulus), rock sole (Lepidopsetta bilineata), Pacific staghorn sculpin (Leptocottus armatus), Pacific tomcod (Microgadus proximus) and the quillback rockfish (Sebastes maliger).

The lesions reported from the liver in this study were descriptive of the cellular changes and no attempt was made to relate these with functional effects in the affected individuals. The lesions were classified as: megalocytic hepatosis; adenomatous foci; cholangioproliferative foci; nuclear pleomorphism and focal hepatocellular hyperplasia - all considered to be toxicopathic on the basis of laboratory animal experiments performed by other investigators. Two additional conditions (hepatic sclerotic foci and heptocellular necrosis) were also noted, but have not been previously reported to be toxicopathic.

Although these authors present no conclusive evidence which would incriminate toxic chemicals as the cause of the lesions, they did show that several of the liver lesions were found in fish which inhabit known contaminated areas such as the Duwamish, Hylebos and Sitcum Waterways, and Commencement Bay. No single abnormality was found consistently in all contaminated areas, but specific areas were frequently associated with a particular abnormality, while the percent incidences were higher in areas of higher concentrations of organic and trace metal contaminants compared to areas relatively free of these chemicals (Table X-9). The total frequencies of liver abnormalities observed in all fish examined in this study (English sole, rock sole, starry flounder and Pacific tomcod), were reported to be statistically greater (at the 0.001 significance level) at stations in the Sitcum Waterway in Commencement Bay and near Harbor Island and the Duwamish River in Seattle than at the other stations sampled.

Pseudobranchial Tumor

Bilateral pharyngeal tumors have been reported in a variety of marine fish including Pacific gray cod (Gadus macrocephalus) (Wellings, 1969), Atlantic cod (G. morhua) (Lange, 1973) and walleye pollock (Theragra chalcogramma). The classification of these neoplasms is uncertain and they have been variously described as adenomas, adenocarcinomas and carcinoid-like tumors. In all instances, however, they occur on the pseudobranch (parabranchial body).

In the Pacific Northwest, pseudobranchial tumors have been reported to occur in epizootic (or perhaps enzootic) proportions among Pacific

TABLE X-9

ANNUAL INCIDENCES OF SELECTED TOXIPATHIC LIVER
ABNORMALITIES OBSERVED IN ENGLISH SOLE FROM AREAS OF PUGET SOUND
(From Malins et al., 1980)

Sampling Area	Incidence of Selected Abnormalities				Total No. of Fish Sampled
	MH[a]	FHH[a]	HAF[a]	CF[a]	
Port Madison	1(3)[b]	1(3)	0	0	29
Sinclair Inlet	0	0	0	0	91
West Point	0	0	0	0	31
Outer Elliott Bay	0	0	0	0	77
Seattle Waterfront	7(9)	1(1)	0	0	82
Duwamish River	25(12)	0	4(2)	1(0.5)	210
Brown's Point	2(6)	0	0	0	32
SW Commencement Bay	0	0	0	0	80
Waterways of Commencement Bay	12(9)	10(7)	1(1)	4(3)	138
Hylebos Waterway	6(5)	6(5)	2(2)	2(2)	129
Budd Inlet	0	0	0	0	70
Case Inlet	0	0	0	0	34

a   MH = megalocytic hepatosis; FHH = focal hepatocellular hyperplasia;
    HAF = hepatocellular adenomatous foci; CF = cholangioproliferative
    foci.

b   Data are expressed as numbers of diseased fish for each type of
    malady. For non-zero incidences, the percentage of the diseased
    fish of the total number examined is included in parentheses.

cod in the Bering Sea (Alpers, et al., 1977). They are of interest, not only for the numbers in which they occur, but also because they are comprised primarily of cells morphologically identical with those found in the epidermal papillomas of pleuronectids.

Grossly, the tumors are generally yellow, have smooth or lobulated surfaces and project from the bony structure of the operculum into the pharyngeal cavity. They are variably vascular and may contain necrotic portions. Frequently remnants of unaffected pseudobranch can be seen as red islets within or on the surface of the lesion. The tumors are comprised predominantly of cells identical to the X-cells of flatfish epidermal papillomas and lie in the fossa which normally contains the pseudobranch. The tumors are frequently divided into lobules separated by fibrous septae.

The tumors elicit little or no inflammatory response and are histologically similar in both East and West Coast species.

Classification of this lesion is complicated by the presence of X-cells. These cells are difficult to classify because they have few or no cytologic specializations common to normal fish cells and because they more closely resemble unicellular parasites. Thus it is unknown whether the lesion represent a true neoplasm or merely a xenoma.

In the Bering Sea, pseudobranchial tumors were reported to occur in 4.2 percent of the Pacific cod sampled (Alpers et al., 1977) and were found in other non-gadid species as well. Similar tumors have also been seen in Pacific cod and in rockfish in Puget Sound (Landolt, unpublished observations) in low numbers. The occurrence of a neoplasm in epizootic proportions always suggests the possibility of an environmental etiology; however, the distribution of this lesion has been poorly correlated with areas of chemical contamination. The affected fish commonly were found in relatively pristine sites and the tumors have not been notably focal geographically. Until more is known about the anatomical nature of the pseudobranchial tumor, little speculation on its etiological nature is possible.

Other Abnormalities in Fish

The recent study by Malins et al. (1980) also identified a number of lesions in other organs of the fish studied, including the gills, kidney, gastrointestinal tract, heart, skin and fins. Many of these lesions were associated primarily with parasite infestations and did not appear to exhibit strong regional trends. By far the most significant lesions in the fish were the cellular changes in the liver discussed above.

Toxic Response of Fish to Contaminants

A literature survey by Malins et al. (1980) identified a number of environmental contaminants, including PCBs, organochlorine and organophosphate pesticides, herbicides, heavy metals and aflatoxin, capable of producing neoplastic and pre-neoplastic lesions in laboratory mammals and fish which resembled some of the lesions observed in fish from Puget Sound. However, these authors did not attempt to compare these results directly with either the concentrations of contaminants or types of lesions observed in the Sound.

Experimental data on the fate of lead and cadmium in a pelagic (coho salmon) and demersal (starry flounder) fish indicated that: 1) both species readily accumulated lead and cadmium from seawater and concentrated them in certain tissues, 2) decrease in water temperature from 10| to 4|C reduced both uptake and depuration of these metals in both species, 3) lead and cadmium were both excreted to some extent via the epidermal mucous of coho salmon, 4) skin and scales acted as storage and possibly detoxification sites in both species, and 5) lead altered the metabolism and disposition of petroleum hydrocarbons in marine fish (Varanasi, 1977).

Studies on the toxic effects of trace metals in West Point sewage treatment plant effluent have shown that the concentrations of lead and cadmium, when diluted to the levels existing at the outfall, were below recommended safe levels (Stober et al., 1977). However, mercury from the effluent was implicated as having exceeded the safe limits and being effective in killing test animals in laboratory bioassays. Copper and chromium also reached high levels in the West Point effluent on several occasions and coincident test fish mortality was reported. Nickel and zinc were found to be consistently below recommended safe standards and more importantly, showed no adverse effects on test animals exposed to various concentrations of these metals from the outfall. No mortalities or other abnormalities have been observed in Puget Sound, which have been conclusively tied to the exposure to ambient trace metals.

INVERTEBRATES AND ALGAE

In addition to oyster mortality, apparently induced by dinoflagellates as discussed previously (Chapter 5), studies have been carried out to determine the effect of metropolitan sewage outfalls on the intertidal macrofauna (Armstrong, 1977) and macroflora (Thom et al., 1977) of Puget Sound. In these studies it was generally concluded that differences between sites (polluted versus clean) were negligible when compared on a similar substrate basis. Even when polychaetes, which are considered indicators of pollution, were examined, they were found in similar numbers on all beaches examined. Differences in algal growth were

attributed to water clarity (availability of light) which was lower at the outfall sites compared to the control sites. This was in part due to increased nutrients in the area encouraging microscopic algal blooms.

In a very limited study of the impacts of PCBs (Krogslund, 1975), no significant differences were observed in the rate of ^{14}C uptake by phytoplankton among stations in the Duwamish River, Elliott Bay and the Main Basin. Similarly, preliminary results indicated that deep subtidal (60 m) macrofauna communities were enriched at the PCB-contaminated dredged-material disposal site in southern Elliott Bay (see Figure IX-6). The increased abundances appeared to be related to substrate and/or the amount of organic matter in the sediments (Dexter et al., 1979).

Mussels (Mytilus edulis) have been examined in the general vicinity of Puget Sound and were found to be free of lesions associated with organic contamination (Lee et al., 1972). The mussels have also been observed growing on pilings located close to the ASARCO effluent discharges (WDOE, 1979). This same species was also examined for its response to PCBs and no lesions or pathological condition were reported as a result of PCB exposure in the laboratory (Calambokidis et al., 1979).

Abnormal mortalities of Pacific oysters at an aquaculture project in Liberty Bay were reported to have been the result of trace metals poisoning, particularly from mercury. Subsequent investigation could not substantiate this claim and implicated algal toxicity (see discussion of Pacific oyster larva toxicity in Chapter 5) and/or bacterial or fungal infection as a more likely cause. No pathological studies were made of the affected oysters (Cummins et al., 1976).

Observations of abnormalities in several species of Puget Sound crustaceans, molluscs, and polychaetes (Malins et al., 1980) indicated that crustaceans have the most frequent and severe lesions, and that these are primarily in the gills, hepatopancreas, connective tissue and bladder. These abnormalities were more prevalent in the most polluted areas (Table X-10), but due to the limited abundance and restricted geographic distribution of these organisms, no absolute correlation with pollution could be made.

SUMMARY

The foregoing discussions can be summarized with the following observations.

No overt toxicopathic effects have been observed in the populations of Puget Sound organisms. While changes have occurred in the abundances of some species, these changes have been related to natural variability and/or physical effects of human activities, e.g., fishing pressure and habitat alteration.

TABLE X-10

ANNUAL INCIDENCE OF SELECTED ABNORMALITIES OBSERVED IN
REPRESENTATIVE BENTHIC CRUSTACEA FROM AREAS OF PUGET SOUND
(From Malins et al., 1980)

| Sampling Area | Shrimp, Pandalus danae | | | | Total No. Examined | HTM | Crab, Cancer gracilis | | | Total No. Examined |
	HN[a]	HV	GN	GMI			HV	GN	BL	
Sinclair Inlet	1(12)[b]	2(33)		0	6	0	2(40)	0	0	5
West Point	0	1(20)		0	5	0	0	0	0	0
Seattle Waterfront	5(56)	3(33)		0	9	2(28)	3(41)	1(15)	1(14)	7
Duwamish River	0	28(68)		3(7)	41	0	2(40)	2(40)	4(80)	5
Waterways of Commencement Bay	3(21)	2(14)		0	14	3(27)	4(36)	1(10)	2(18)	11
Hylebos	8(18)	23(51)		4(9)	45	1(10)	6(60)	0	2(20)	10
Budd Inlet	0	1(25)		0	4	0	4(57)	0	0	7
Case Inlet	0	0		0	8	0	3(43)	0	0	7

a   HN = hepatopancreatic necrosis; HV = vesicular hepatopancreas; GN = melanized nodules in the gills; GMI = mycotic gill infection; HTM = hepatopancreatic tubular metaplasia; BL = bladder lesions.

b   Data are presented as the numbers of diseased organisms observed, with the percentage of diseased fish of the total examined, included in parentheses for non-zero values.

A number of tissue lesions of varying severity have been observed in demersal fish and crustacea. The incidences of many of these lesions appeared to be greater in organisms caught in contaminated areas, and hence presented an implied causal relationship. However, no specific chemical agent(s) has been identified, nor have other non-chemical agents been clearly eliminated, as the cause of the lesions. In addition, the observed focal distributions of the diseases must be qualified for a number of reasons.

First, while the percentages of diseased fish have been observed to be greater in the contaminated areas, major variability in the incidences between samplings has also been noted, as well as differences in the species monitored. These variations make it difficult to clearly (statistically) infer focal distributions of the diseases at the present level of study.

Secondly, the available data do not clearly elucidate what may be pertinent ecological relationships. The waterways are undoubtedly different environments than many other areas of the Sound. For example, tidally and river-induced currents may be stronger, salinity variations are probably greater, and shore construction has essentially eliminated the littoral zone. These factors may be important in generating an apparent increase in the percentages of diseased fish, for example, by favoring greater percentages of larger, older fish. In addition, secondary effects may occur such as "natural" stresses, e.g., salinity shock or nutritional deficiencies from limitations on the availability of some foods, which may in turn increase the organisms' susceptibility to disease.

Finally, it must be recognized that the migratory habits of the populations which have been studied are poorly established (see Chapter 6). The catch statistics, variable disease incidence, as well as the high variability in the concentrations of contaminants observed in the organisms from the affected areas (Malins et al., 1980) appear to reflect some migration of the test organisms. As a result of these factors, it is presently difficult to determine the history of movement of either healthy or diseased fish. Thus it is possible that:

1. the diseased fish are long-term residents of the contaminated areas and the diseases do in fact result from the long-term exposure to contaminants or some other area-specific factor. Variability in the incidences may reflect temporary influxes of healthy fish.

2. toxicants may rapidly induce the diseases in fish which enter the contaminated areas. This possibility would seem to require increased susceptibility with age, since the lesions are noted predominantly in older fish.

3. the contaminated areas represent preferred habitats for diseased fish, e.g., resulting either from the physical factors discussed above or possibly reduced predation of affected fish.

4. disease induction is equal in all areas of the Sound, but higher predation on diseased fish away from the industrialized areas, e.g., by seals, results in an apparent increase in the industrialized areas.

5. the incidence of disease is not greater in the contaminated areas and the data result from coincidental variations and/or sampling artifacts.

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CHAPTER 11. CONCEPTUAL REPRESENTATION OF

TOXICANT TRANSPORT AND FATE

INFORMATION FOR ASSESSING ASSIMILATIVE CAPACITY

The discussion in the previous chapters addresses two aspects important to the normal functioning of the Puget Sound ecosystem: Transport and fate of toxicants, and biological abnormalities. Although there is no documented cause-effect relationship between ambient concentrations of toxicants and the observed biological abnormalities, these aspects are of critical importance in determining the assimilative capacity of Puget Sound for toxicants.

Assimilative capacity is defined as the maximum amount of a toxicant the system can process through the pathways discussed in Chapters 8 and 9 without disruption of its normal ecological relationships. Three categories of information are required to determine assimilative capacity and are based on ecosystem considerations. They consist of: input/output rates, rates of internal redistribution (physical, chemical, and biological) and response/effect relationships. The first two categories of information characterize the biological availability of toxicants. The status of knowledge for this information is presented below. The third category of information is the most difficult to estimate at the process level as is demonstrated below. For a dynamic estuarine environment such as Puget Sound, these properties are not well documented, due to their complexity as discussed in Chapter 7. For many of the toxic compounds found in the Sound and mixtures of them, very little is known of biological responses. Also, the ability of marine organisms to recover after exposure is largely unknown. Even though these limitations are accepted, it is tacitly recognized that without a conceptual framework at the process level, such as the one presented below, and without knowledge of the resistence and resilience of biological organisms to the biologically available toxicant concentrations, the effects of perturbations induced by a toxicant input cannot be assessed properly.

TRANSPORT AND FATE PROCESSES

Generic transport schemes for trace metals and organic contaminants as applied to Puget Sound were presented in Chapters 8 and 9. The conceptual representation developed here is more detailed than the individual schemes discussed earlier and has been organized to facilitate cross-referencing each functional element with the relevant information provided throughout the report. This representation can be considered

as a model both conceptual and diagnostic in its utility. It is conceptual in the sense of representing components and processes specific to the dynamics of toxicants in the Puget Sound ecosystem. It is diagnostic in the sense of characterizing the relationships of the processes. It allows testing the validity of each process and/or pathway with acquired data and/or identifying data gaps and information needs to quantify each element.

The basic functional elements of this representation are displayed under three main categories and major subgroups as shown in Figure XI-1. This structuring is not intended as an ideal ecological interactive flow network, but as a means to facilitate visual examination and accounting of processes and pathways by conceptualizing them in distinct packets of information which can be accessed in the various chapters of this report.

Input processes are rated according to their significance in the introduction of trace metals and organic compounds to Puget Sound as shown in Table XI-1. The available data and analyses summarized in Chapter 8 suggest that natural sources--riverine inputs, advective transport, and shoreline erosion--make the greatest contribution of trace metals. Sources of synthetic organic compounds are poorly known, although advective transport, accidental spills, and dredging disposal/resuspension may be important. Most have an ultimate industrial origin (Chapter 9).

The rating of receiving water processes relative to their contribution to the overall transport and fate of the same categories of toxicants is shown in Table XI-2. Physical/chemical processes dominate over biological processes for both trace metals and organic compounds. Advection contributes to the transport and distribution via movement of water masses across subregions of Puget Sound containing the toxicants in both dissolved and suspended particulate forms, and flushing from the Sound constitutes one of the dominant pathways for toxicant removal. Sorption/partitioning on available particulate material (abiotic as well as biotic) is high for organics and may be important as a boundary process for trace metals. Since most of the suspended particulates have greater density than that of seawater, sedimentation is also a dominant pathway for toxicant removal with the sediments providing one of the ultimate sinks for these toxicants. Toxicant mobilization through resuspension is not a well-documented process in Puget Sound but could be significant as a redistribution mechanism of fine particles from erosional to depositional areas. Chemical transformations for trace metals resulting from reduction/oxidation reactions have been poorly documented but may constitute a system-wide pathway of mobilization. For trace organic compounds this mechanism is also not well documented. Although some compounds (PCBs) show no apparent evidence of noticeable chemical transformation, the distribution and relative concentrations of arenes in sediments cannot be completely explained based on direct input and may imply in situ chemical or biochemical reactions.

TABLE XI-1

RATING OF INPUT PROCESSES RELATIVE TO
TOXICANT LOADING IN PUGET SOUND*

Input Function	Trace Metals				Trace Organics (PCBs)				Reference in Text**
	H	M	L	NR	H	M	L	NR	
Dry Fallout			X				X		Ch 8,9
Gaseous Exchange			X				X		Ch 8,9
Precipitation			X				X		Ch 8,9
Riverine Transport	X					——			T·VIII-8, Ch 9
Advective Transport	X							X	T·VIII-8, Ch 9
Municipal Discharge		——				——			T·VIII-8, Ch 9
Industrial Discharge		X						X	T·VIII-8, Ch 9
CSO Discharge			X				X		T·VIII-6, T·IX-9
Storm Drain Discharge			X			——			T·VIII-6, T·IX-9
Shoreline Erosion	X						X		T·VIII-8, Ch 9
Accidental Spilling		——			X				Ch 8,9
Dredge/Disposal		——				——			Ch 8,9
Random Discharges			X					X	Ch 8,9

*H, M, L refer to High, Medium and Low importance, respectively.

**Ch and T refer to Chapter and Table, respectively, as presented in the main body of the report.

NR - Not rated due to lack of information.

TABLE XI-2

RATING OF RECEIVING SYSTEM PROCESSES CONTRIBUTING TO THE OVERALL TRANSPORT AND FATE OF TOXICANTS IN PUGET SOUND*

Process	Trace Metals				Trace Organics				Chapter
	H	M	L	NR	H	M	L	NR	
Boundary				X				X	8,9
Physical/Chemical									
Advection	X				X				8,9
Sorption/Partitioning			X				X		8,9
Sedimentation	X				X				8,9
Resuspension				X				X	4,8,9
Chemical Transformation				X		———			8,9
Biological									
Accumulation from abiotic matrix:									
Water		X				X			8,9
Sediment		X				X			8,9
Biomanipulation of sediment (bioturbation, subsurface irrigation)				X				X	NI
Food Web Transport		X					X		7,8,9
Biochemical Transformation		X				———			8,9
Depuration/Excretion				X				X	NI

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*H, M, L refer to High, Medium and Low importance, respectively.

NR - Not rated due to lack of information

NI - Not included

The biological processes, in general, are of only medium to low importance in influencing the overall transport and distribution of trace metals and trace organics in Puget Sound. The concentrations within the organisms of both trace metals and organics appear to reflect the concentrations observed in the ambient environment, although the actual modes of accumulation are not well established. At natural levels, most trace metals are important micronutrients and, with the exception of mercury, do not appear to accumulate to high levels in biological tissue (Table XI-3). In comparison, few, if any, anthropogenic organic compounds are directly utilized in natural systems. The concentrations of the organic compounds observed in biological organisms are often a complex function of the ambient levels, the rates and modes of uptake, and the rates and modes of depuration. For example, as noted in Chapter 9, PCBs are hydrophobic and resistant to metabolism, and as a result accumulate to high levels in all nonaqueous phases; while many arenes are similarly hydrophobic but apparently can be metabolized and thus eliminated, at least by fish and other higher organisms. Irrespective of the levels to which the contaminants accumulate within the biological organisms, a major point which must be noted is that in all areas of the Sound, the total amount of biomass is very small compared to the abiotic phases. As a result, the total amount of toxicants transported and affected by the biological phase is also small.

Biological manipulations of sediments (e.g., bioturbation, subsurface irrigation) may also effect toxicant concentrations and distributions. There is no evidence to date that such processes are significantly influencing toxicant distributions in Puget Sound. The complexity of food webs (Chapter 9) and the shortage of the necessary toxicant concentration data for specific trophic levels makes conclusions regarding the importance of food web processes to toxicant transport and fate tentative at best. The data summarized in Table XI-3 indicate that with the possible exception of mercury, the accumulation of trace metals in higher trophic levels of both pelagic and benthic food webs is not significant. Although the data in Table XI-4 are limited to only hydrophobic compounds (see Chapter 9), the same conclusion can be made for accumulation to upper trophic level biota with the exception of air-breathing organisms (e.g., marine mammals and birds).. No evidence exists to suggest that biochemical transformations influence either trace metal or synthetic organic distributions in Puget Sound. However, as noted earlier, arene concentrations measured in sediment cores do not appear to be explained by direct input considerations. Metabolism of arenes by bacteria and resident biota could be a possible explanation for this trend, although no evidence exists.

Quantitation of each functional element of the conceptual representation is currently not possible due to the lack of sufficient data for each element. A summary listing of the data needs and data

TABLE XI-3

SUMMARY OF SELECTED TRACE METAL CONCENTRATIONS IN
VARIOUS MARINE PHASES OF THE MAIN BASIN, PUGET SOUND

| Marine Component | Concentration Units | Mean Concentration | | | | Reference |
		Cu	Pb	Zn	Hg	
Water	µg/ml	0.0004	NA	0.002	NA	Table VIII-2
Suspended Particulates	µg/ml	171	220	399	NA	Table VIII-2
Sediments	µg/g	35	21	87	0.06	Table VIII-1
Pelagic Biota	µg/g-wet wt					Table VIII-9
Zooplankton		4	1	10	0.002	
Fish (dogfish muscle)		2	0.5	1	0.97	
Benthic Biota	µg/g wet wt					Table VIII-9
Molluscs		3	1	29	0.03	
Fish (muscle)		0.3	0.5	7	0.07	

NA - Not available

TABLE XI-4

SUMMARY OF CONCENTRATIONS OF PCBs, ARENES AND CBDs
IN VARIOUS MARINE PHASES FROM PUGET SOUND

Marine Component	Concentration Units	Approximate Mean Concentration			Reference
		Total PCBs	Total Arenes	Total CBDs	
Water	μg/ml	4×10^{-6}	80×10^{-6}	ND	Table IX-3,4
Suspended Particulates	μg/g	0.1	3	ND	Table IX-3,4
Sediments	μg/g	0.2	0.8	<0.01	Figure IX-1
Pelagic Biota					
Zooplankton	μg/g dry wt	0.8	NA	NA	Table IX-7
	μg/g lipid wt	4[a]	NA	NA	Table IX-11
Fish	μg/g lipid wt	5[d]	NA	NA	Table IX-11
Seal	μg/g blubber	31[b]	NA	NA	Table IX-9
Benthic Biota					
Shrimp	μg/g dry wt[c]	0.3[c]	0.1	0.01	Table IX-7
Fish	μg/g lipid wt	7[d]	NA	NA	Table IX-11
	μg/g dry wt livers[c]	3	ND	0.004	Table IX-8

[a] Whidbey Basin

[b] Hood Canal

[c] Port Madison

[d] Average of Hood Canal and Southern Sound

NA - No data available

ND - Below detection limits

availability to develop a quantitative version of the conceptual scheme depicted in Figure XI-1 is summarized in Table XI-5. This analysis is based on available sources as presented in Chapters 8 and 9. It is apparent that for other than physical/chemical processes the information necessary to quantify the biologically mediated fate of toxicants in Puget Sound is nonexistent.

ASSESSING THE ASSIMILATIVE CAPACITY

Given these limitations in knowledge, the determination of assimilative capacity appears to be virtually impossible at this time. It is, therefore, apparent that methods for estimating the assimilative capacity of Puget Sound for toxic chemicals must rely for the near term on causal relationships which, in turn, depend upon parameters that can be easily measured in the environment and which reflect the net effects of complex intermediary transport and chemical transformation processes. In essence, these relationships must link the concentrations of the toxic chemicals to an observed effect. The significance of the effect to our society depends upon the value judgments of the public and environmental decision makers of the region.

For the purpose of this report only a generic plan was developed to guide the formulation of these relationships. This plan is summarized in Table XI-6 in terms of modular study components, each having specific information outputs that contribute to the overall development of the relationships.

It is doubtful that current scientific techniques can develop an unequivocal cause-effect relationship between any biological effect and exposure to a toxic chemical, particularly considering the limited analytical and toxicological capabilities for defining causative agents. At the same time, a research program could proceed based on the study components in Table XI-6 to the point of developing rigorous statistical correlations between implicated biological effects, for example, some of the maladies discussed in Chapter 10, and the concentrations of specific toxic chemicals, as well as testing for the induction of these effects through direct exposure of organisms to the ambient suite of toxicants extant in the Sound. Given the results of the correlations and direct exposure tests, it can be established whether or not toxic chemicals at concentrations and in the mixtures found in the Sound can induce any biological response. Such data should be suitable for directing further research on a limited and cost-effective basis and at the same time provide strong implications of causation, which might be sufficient to initiate regulatory and corrective measures prior to the onset of serious and/or irreversible biological damage.
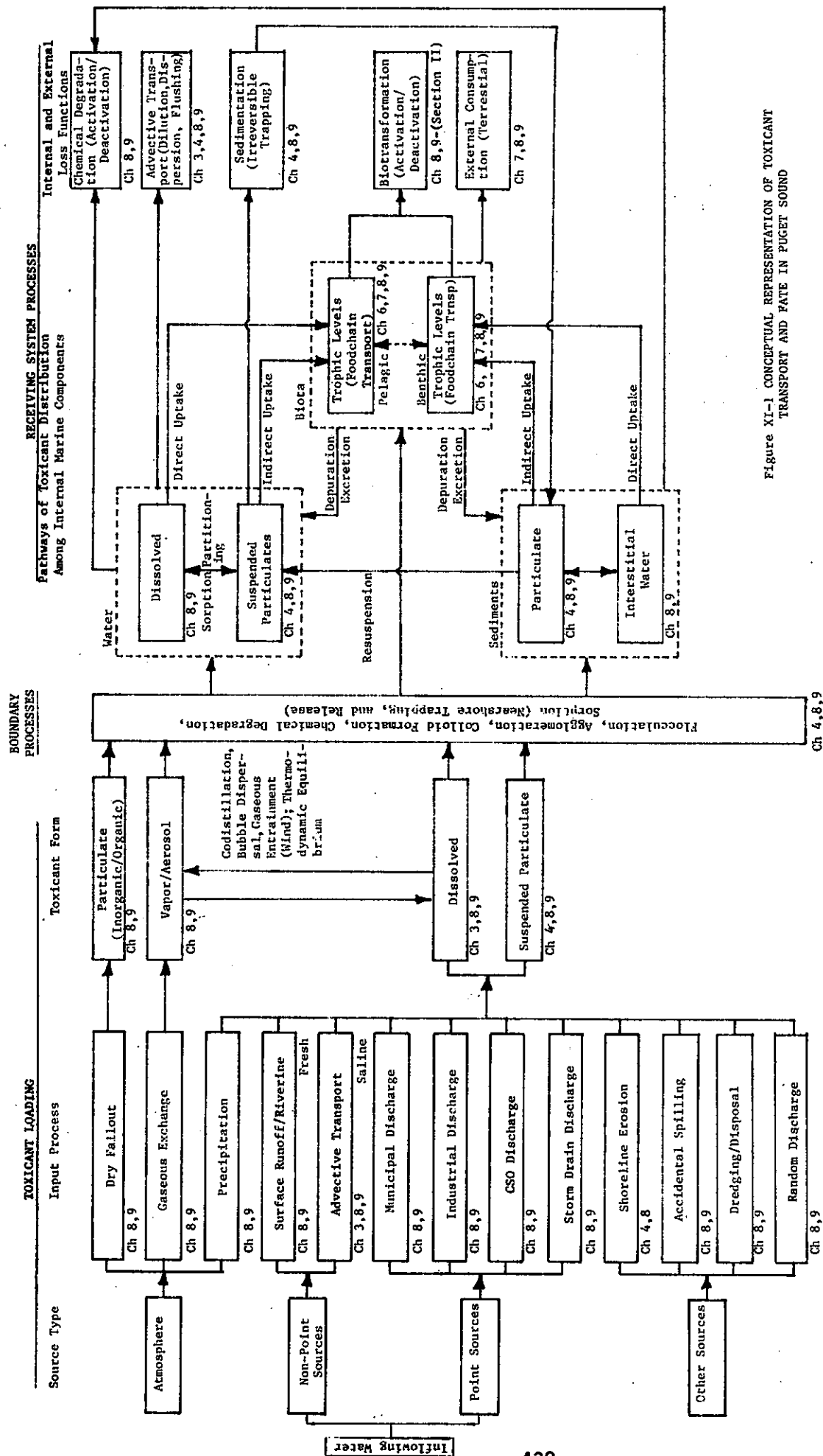
Figure XI-1 CONCEPTUAL REPRESENTATION OF TOXICANT TRANSPORT AND FATE IN PUGET SOUND

TABLE XI-5

INFORMATION NEEDS AND DATA AVAILABILITY FOR GENERATING A
QUANTITATIVE MODEL FOR TRANSPORT AND FATE IN PUGET SOUND

Model Component	Information Input	Data Availability RA	PA	NA	Information Output
PHYSICAL/CHEMICAL					
Toxicant-Inputs	Identification of chemical types and sources		———		Spatial and temporal definition of toxicant loading
	Source locations and intensities (mass loading and concentrations)		———		
Boundary Processes	Flocculation/ agglomeration rates			X	Nearshore trapping and release of toxicants
	Colloid formation rates			X	
	Chemical transformation rates			X	
Advection	Mean currents	X			Definition of toxicant mass/ volume exchange across boundaries; temporal variability; spatial distributions; residence times; flushing
	Concentrations of toxicants (particulate/ dissolved)		———		
	Vertical and lateral mixing rates		———		
	Water mass and sediment transport	X			
Sorption/ Partitioning	Concentrations of toxicants on suspended particles and sediments		———		Toxicant exchange between particulate and dissolved forms; removal rates of toxicants from water; transport across interface
	Partition coefficients		———		
	Equilibration rates; organic content; particle size; surface energetics; toxicant solubility		———		

TABLE XI-5 (Continued)

Model Component	Information Input	Data Availability RA PA NA	Information Output
Sedimentation/ Resuspension	Particulate flux to bottom sediments	————	Toxicant flux to bottom sediments; mobilization and redistribution
	Suspended particle distribution	X	
	Sedimentation/ resuspension rates (nearshore/offshore)	————	
	Concentrations of toxicants (particulate); particle size	————	
Chemical Transformation	Toxicant specific reaction rates (water column, solid/water interface, sediments); redox conditions in bottom sediments	X	Toxicant loss through chemical reactions (toxicant and toxicant class specific)

BIOLOGICAL

Model Component	Information Input	Data Availability RA PA NA	Information Output
Accumulation from Abiotic Matrices	Accumulation factors (biota/water); toxicant concentration in tissues and sediments; uptake and depuration rates	————	Direct and indirect uptake; body burden projections
Sediment Biomanipulation	Toxicant recycling rates at sediment/water interface and bioturbation depths	X	Redistribution and mobilization of toxicants within subsurface sediment layers
Food Web Transport	Toxicant concentrations; predator/prey mass ratios; ingestion rates; assimilation rates; excretion rates	X	Toxicant accumulation at higher trophic levels
Biochemical Transformation	Body burden; biotransforming enzyme activities (toxicant specific)	X	Biologically induced loss and/or production of toxicants; activation/ deactivation

RA, PA, NA refer to Readily Available, Partially Available, and Not Available, respectively.

TABLE XI-6

INFORMATIONAL NETWORK FOR DEVELOPING CAUSE/EFFECT
RELATIONSHIPS IN PUGET SOUND

Study Component*

Toxicant Loading Computations	Documentation of input levels of toxicants by individual compounds as well as by chemical classes
Diagnostic Modelling of System Behavior	Definition of system's dynamics; identification of system characteristics associated with vulnerability, e.g., sites of potential toxicant accumulation, restricted circulation patterns
Definition of Internal Pathways for Redistribution and Processing of Toxicants	Ambient toxicant concentrations in aquatic components; recycling and storage potential; partitioning among biotic and abiotic marine components
System Definition and Classification	System vulnerability ranking in terms of ecosystem types, properties of toxicants and water use designations
Community Impact Analysis (Determination of Stress Indicators)	Spatial and temporal behavior of community structure; pattern development correlating toxicant levels to structural changes within the community
Site Specific Toxicity Testing	Screening of contaminated substrates for determining lethal and sublethal effects of ambient toxicant levels; determination of etiology of observed biological abnormalities
Dose-Response Curve Development	List of toxicant threshold concentrations responsible for causing changes in ecological indicators

*Each component can be considered an integral part of the informational network necessary to determine the assimilative capacity of the system.